Title

Appendix H: The Lifecycle of Materials: An Appendix to the Report, “A Lifecycle Emissions Model (LEM): Lifecycle Emissions From Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials”

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INTRODUCTION

Overview

This appendix analyzes the energy and emissions associated with the lifecycle of materials and automobiles. I present first an overview of methods and results. Next, I discuss the materials composition of motor vehicles. This is followed by detailed information about each of the major materials, including descriptions of manufacturing processes, tabulations of energy and emissions data, data sources, and other information on the industry. Next, I discuss energy use in and emissions from the assembly of motor vehicles and the transportation of raw materials, semi-fabricated products, and motor vehicles. Finally, I discuss energy used to make agricultural chemicals. I give special emphasis to materials used in automobiles.

Materials in the Lifecycle Emissions Model (LEM)

The LEM currently represents emissions from the following uses of materials:

- steel, aluminum, plastics, and other materials used in light-duty vehicles
- steel, aluminum, plastics, and other materials used in heavy-duty vehicles
- steel, aluminum, plastics, and other materials used in fuel-storage tanks fr vehicles
- steel, aluminum, plastics, and other materials used in batteries for vehicles
- steel, aluminum, plastics, and other materials used in fuel cells for vehicles
- limestone used to scrub sulfur dioxide emissions from coal-fired power plants
- limestone used to scrub sulfur dioxide emissions from coal-fired industrial boilers
- concrete and cement displaced by uses of the ash and other byproducts of coal combustion and scrubbing
- the use of cement to make concrete
- sulfuric acid coproduct of the copper manufacturing process
- refractories (high-temperature bricks) consumed in the production of steels
- concrete used to plug oil and gas wells
- sulfuric acid used in the production of alternative fuels
- agricultural chemicals (mainly fertilizers)

I focus mainly on materials used in motor vehicles because this consumes more energy and results in more emissions than do any of the other uses of materials listed here.

The LEM represents international trade in materials, as part of the calculation of lifecycle emissions from the use of materials, because for several reasons the source of materials might affect the calculation of emissions. First, the energy intensity of and hence emissions from materials production is higher in some countries than in others. (Thus, if the U. S. imports more material from Mexico, and less from Canada, and the energy intensity of materials production is relatively high in Mexico, emissions

attributable to material use in the U. S. will increase.) This is discussed in this appendix. Second, the mix of fuels used to generate the electricity used in the aluminum production process or the vehicle assembly process can vary widely from country to country. (Norway uses mainly hydro power, whereas Russia uses mainly fossil fuels , so to the extent that a country imports aluminum from Norway rather than Russia, emissions will be lower.) This also is discussed in this appendix. Third, emissions associated with the international transport of materials depend on distances between producing countries and consuming countries. The method of calculating these emissions is discussed in this appendix; data on international trade in materials for the U. S. and other consuming countries is discussed in Appendix B. Fourth, some accountings of greenhouse-gas GHG) emissions distinguish domestic from foreign or international emissions. The methods for doing this are discussed in the main report and in Appendix B.

Background on materials in motor vehicles

The manufacture of materials for motor vehicles requires a considerable amount of energy and produces substantial emissions. A recent study performed by the main U. S. automakers indicates that the material production and manufacturing stages consume 14% of the energy consumed in the entire life of a "generic" U. S. family sedan (Sullivan et. al., 1998). That study also estimates that significant amounts of the life cycle emissions occur in material production and manufacturing (Table H-1).

There are many materials used in the modern automobile, but the dominant material remains steel (see Table H-2)[1]. The percentage of other materials such as aluminum and plastics has increased steadily over the years as automakers have been making cars lighter to improve fuel economy. This trend is expected to continue into the future. In this analysis, we pay particular attention to aluminum and steel. Unfortunately, the publicly available information on plastics does not allow the same detailed characterization of these materials as for steel and aluminum.

An analysis of the lifecycle of materials and automobiles can inform evaluations of tradeoffs involved in fuel-economy policies. For example, one can improve the fuel economy and hence reduce the energy use of motor vehicles by making them lighter, but some lightweight parts, such as aluminum and plastics, take more energy to produce than do the steel parts that they will replace. A lifecycle analysis can compare the energy and emissions saved by higher fuel economy due to the use of lighter materials with the extra energy and emissions in the production of the lighter materials.

Because it takes much much less energy to recycle post-consumer materials back to finished materials than to produce finished materials from virgin feedstocks, the treatment of recycling is in an important part of lifecycle analyses of materials. Both

[1] Table H-2 also shows, for each material, the ratio of material use in automobiles to total consumer use of the material. A material industry for which 10 percent of sales are to automobile manufacturers will be much less responsive to the automotive industry than will producers of a material for which the automotive industry makes up more than half of their consumer base.

aluminum and steel are easily recyclable. By contrast, plastic is much less recyclable, and as a consequence, plastics currently make up much of the portion of discarded automobiles that go to landfills.

METHODS OF ANALYSIS

General

The Lifecycle Emission Model (LEM) estimates emissions of urban air pollutants and greenhouse-gases (GHGs) from the lifecycle of fuels and materials used in motor vehicles. The lifecycle of fuels is discussed in the main documentation report to which this is an appendix. This appendix discusses the lifecycle of materials in the LEM.

The LEM reports emissions per mile in two general categories: motor vehicle assembly and transport, and motor-vehicle materials. Formally:

$$EMA_P = \frac{\left(ERVA_P + ERT_{V,P}\right) \cdot LB_V + \sum_M ERML_{M,P} \cdot LB_{M,V}}{LVMT} \qquad \text{eq. H.1}$$

where:

$EMA_{P,}$ = emissions of pollutant P from motor-vehicle assembly and materials, expresssed per mile of travel (g-P/mi)
$ERVA_P$ = emissions of pollutant P from vehicle assembly, per lb. of vehicle (g-P/lb.-vehicle) (discussed below
$ERT_{V,P}$ = emissions of pollutant P from vehicle and parts transport, per lb. of vehicle V (g-P/lb.-vehicle) (discussed below)
$ERML_{M,P}$ = total lifecycle emission rate of pollutant P per lb. of finished material M, over the lifecycle of material M (g-P/lb.-M) (discussed below)
$LB_{M,V}$ = weight of material M in a motor vehicle (lbs.) (Table H-3)
LB_V = weight of motor vehicles (lbs.) (Table H-3 and the main documentation report)
LVMT = lifetime travel by motor vehicles (mi) (discussed in the main documentation report)

This appendix focuses on the estimation of emissions per lb. from the lifecycle of materials (ERML in eq. H.1). It also discusses emissions from vehicle assembly (ERVA) and from the transport of vehicles and parts (ERT).

Materials

The objective of this lifecycle analysis of materials is to estimate emissions of criteria pollutants and GHGs (carbon monoxide [CO], non-methane organic compounds [NMOCs], methane [CH_4], nitrogen oxides [NO_x], nitrous oxide [N_2O], sulfur oxides

[SO_x], particulate matter [PM], carbon dioxide [CO_2], chlorofluorocarbons [CFCs], and perfluorocarbons [PFCs]) from the production, transport, use, and recycling of finished materials and their feedstocks. Emissions are expressed in grams of pollutant per unit weight (usually a lb.) of *finished* material used. Because in most cases most emissions of CO_2 and other pollutants come from the use of energy, fuel and electricity-use data are an important part of the lifecycle emissions calculations. Thus, in the Lifecycle Emissions Model (LEM) for which this appendix is partial documentation, energy use is an important intermediate parameter, but not a final reported result.

Emissions related to the lifecycle of materials in vehicles are calculated as the product of emisions per lb. of each finished material multiplied by the quantity of each material in a vehicle. Information on the quantity of materials in motor vehicles is provided in Table H-3 and in the main report. Estimates of emissions per lb. of each finished material are developed in this appendix. The nature of the available data lead us to categorize several sources of emissions in the lifecycle of materials:

- energy use (electricity): lifecycle emissions related to the use of electricity;
- energy use (fuels): lifecycle emissions from the use of coal, oil, or natural gas in industrial boilers that provide process heat at various stages in the lifecycle of materials;
- energy use (transportation fuels): lifecycle emissions from the use of petroleum fuels to transport finished materials and motor vehicles to end users;
- non-energy inputs: lifecycle emissions from the use of other inputs (such as bulk chemicals) to the material-production lifecycle;
- other "process area" emissions: emissions from processes or activities that are not associated with the use of electricity, fuel for industrial boilers, or any of the inputs already fully characterized as part of the third group in this list.
- a "scrap recycling credit" that accounts for the recycling of clean manufacturing scrap instead of producing more "virgin" products from raw materials

We make a category for emissions related to energy use because energy use typically is the largest source of emissions (especially of GHG emissions) in the materials lifecycle, because data on energy usage rates are usually available, and because general emission factors for industrial boilers are available. We characterize transportation emissions separately in order to be able to explicitly represent shipping distances, shipping modes, and international trade in materials. We establish a separate

"non-energy inputs" category because in some cases these other inputs are important, and the emission factors and hence lifecycle emissions associated with these other inputs are different from those associated with energy inputs. We establish a "process-area" emissions category because emissions from some stages in the lifecycle of materials are given in the available sources as belonging to particular processes rather than to separately characterized inputs. Finally, we create a "scrap recycling credit" because the production of materials from manufacturing scrap takes less energy and hence produces less emissions than does production from raw materials.

Electricity-related emissions are equal to electricity usage rates multiplied by electricity-use lifecycle emission factors. Fuel-related emissions are equal to fuel-use rates for each kind of fuel multiplied by lifecycle emission factors for each kind of fuel in industrial boilers. (Transportation-related emissions are discussed later in this appendix.) The lifecycle emission factors are calculated in detail in the LEM (see DeLuchi, 1993, and the main LEM documentation). Other-input emissions are equal to input usage rates multiplied by lifecycle emission factors documented here or in the main report. Process-area emissions per lb. are input directly on the basis of emissions studies, reviewed below.

Energy and other inputs are summed over all stages of the materials lifecycle, from raw material extraction to primary materials manufacturing.

Formally:

$$ERML_{M,P} = EEN_{M,P} + EOI_{M,P} + EDC_{M,P} + EPR_{M,P} + SRC_{M,P} + EOLRC_{M,P} + ETR_{M,P}$$

eq. H.2

$$EEN_{M,P} = ENEF_{F,P} \cdot \sum_{L} ENR_{F,M,L} \qquad \text{eq. H.3}$$

$$EOI_{M,P} = OIEF_{I,P} \cdot \sum_{L} OIR_{I,M,L} \qquad \text{eq. H.4}$$

$$EPR_{M,P} = \sum_{L} EPR_{M,P,L} \qquad \text{eq. H.5}$$

where:

ERML is defined above

$EEN_{M,P,}$ = lifecycle emissons of pollutant P from the use of energy (electricity and fuels) in the production of finished material M, excluding energy use in transportation finished material to end users (grams-P/lb.-finished-M)

$EOI_{M,P,}$ = lifecycle emissons of pollutant P from the use of non-energy inputs in the production of finished material M (grams-P/lb.-finished-M)

$EDC_{M,P,}$ = the "coproduct emissions displacement credit": lifecycle emissons of pollutant P displaced by the marketing of coproducts in the production of material M grams-P/lb.-finished-M) (discussed below)

$EPR_{M,P,}$ = emissons of pollutant P from process areas in the lifecycle of material M, per unit of finished material output (grams-P/lb.-finished-M; see Table H-8 for results aggregated over all stages of the lifecycle)

$SRC_{M,P,}$ = the "scrap recycling credit": reduction in emissions of pollutant P from the lifecycle of material M due to the use of manufactured scrap instead of raw materials (grams-P/lb.-finished-M) (discussed later in this section)

$EOLRC_{M,P,}$ = the "end-of-life recycling credit": the reduction in emissions of pollutant P from the lifecycle of material M due to the use of recycled post-consumer material instead of raw materials (grams-P/lb.-finished-M) (discussed later in this section)

$ETR_{M,P,}$ = lifecycle emissons of pollutant P from transportation of finished material M to end users (grams-P/lb.-finished-M) (discussed later in this appendix)

$EPR_{M,P,L}$ = emissons of pollutant P from process areas in stage L of the lifecycle of material M, per unit of finished material output (grams-P/lb.-finished-M.; these are input directly, on the basis of studies reviewed below; see Table H-8 for results aggregated over all stages of the lifecycle)

$ENEF_{F,P}$ = lifecycle emissions of pollutant P from the use of a unit of fuel F in the production of materials (grams-P/BTU-F) (discussed in the main text and in DeLuchi [1993]; note that electricity emission factors are based on 3412 BTU/kWh)

$ENR_{F,M,L}$ = energy-usage rate: BTUs of fuel F input at stage L of the lifecycle of material M, per unit of finished material M produced (BTUs-F/lb.-finished-M.; see Table H-6 for results aggregated over all stages of the lifecycle, for the U. S.; see the section below for a discussion of how this parameter is estimated for other countries) (note that in the LEM, electricity input is measured at 3412 BTU/kWh)

$OIEF_{I,P}$ = lifecycle emissions of pollutant P from the use of a unit of input I in the production of materials (grams-P/unit-I; input units depend on the type of input) (discussed in Table H-6, or in the main report for which this is an appendix, or in DeLuchi [1993])

$OIR_{I,M,L}$ = other-iput usage rate: units of input I to stage L of the lifecycle of material M, per unit final output of finished material M (input-I/lb.-finished-material; input units depend on the type of input) (see Table H-6 for results aggregated over all stages of the lifecycle)

$EPR_{M,P,L,}$ = emissons of pollutant P from process areas in stage L of the lifecycle of material M, per unit of finished material output (grams-P/lb.-finished-M; these are input directly, on the basis of studies reviewed below; see Table H-8 for results aggregated over all stages of the lifecycle)

subscript M = finished materials (see e.g. Table H-3)

subscript P = pollutants (NMOCs, CH_4, CO, NO_x, N_2O, SO_x, PM, CFCs, PFCs, and CO_2-equivalents)
subscript L = stages of the lifecycles (resource extraction, primary raw material processing [sometimes several steps], transportation, secondary material processing [recycling])
subscript F = fuels used to provide energy in the materials lifecycle (coal, oil, gas, electricity)
subscript I = other (non-energy) inputs (see tables on individual materials, below)

In all cases, electricity is an energy input, and is treated as such (parameter ENEF). In most *but not all* cases, petroluem, coal, and natural gas are energy inputs (parameter ENEF) – they are combusted at high temperature to provide energy to do work somewhere in the lifecycle. However, in some cases, petroleum, natural gas, or coal are used in chemical processes other than high-temperature combustion intended to provide heat energy for work (parameter OIR). For example, the commercial production of metals requires carbon as a reducing agent (IPCC, 1997); in some cases, this carbon comes from coal. Now, in the LEM, the emisson factors used for high-temperature combustion of fossil fuels (parameter EF in eq. H.3) are those for combustion industrial boilers. Given that the use of coal as a reducing agent is not like high-temperature combustion of coal in industrial boilers, it would be incorrect to treat coal used for chemical reduction as if it were coal burned in an industrial boiler. Hence, the LEM has a set of lifecycle emission factors specifically for the use of coal to make coke.

Note that emission factors for energy use (EEN), transportation (ETR), and other inputs and outputs (EOI) include all stages of the lifecycle for the fuel or other inputs. They also include a complete carbon balance.

Process area emissions (parameter EPR) are those from a specific process within the materials lifecycle. In the case of the aluminum lifecycle, for example, emissions from the chemical reduction of alumina to aluminum are estimated as non-combustion process-area emissions. Process-area emissions also are estimated as part of a complete carbon balance for some processes; e.g., to acocunt for the difference between carbon in a feedstock raw material and carbon in a finished product.

This method (eqs. H.2 to H.6) is used to estimate emissions from the production of finished materials from raw feedstocks ("virgin" or "primary" production) and from recycling ("secondary" production). Note that in the case of primary or virgin production, *the "lb." in the denominator of the ENR (BTU/lb.), OIR (other-input/lb.) and EPR (g/lb.)parameters is a pound of finished material produced from raw materials without any recycling of manufactured scrap.* The effects of recycling clean manufactured scrap are handled separately by the parameter SRC in eq. H.2.

This appendix reviews data on the energy and other input usage rates (ENR and OIR in eqs. H.3 and H.4) and process-area emissions (EPR in eq. H.2). The information in this appendix is based on a review of the publicly available literature. In many cases,

estimates of energy use and emissions vary widely from source to source. I present the range of values in the literature, and where necessary make my best estimate.

Adjustments for different energy intensities in other countries

As mentioned above, the LEM represents international trade in steel, aluminum, plastics, other materials, and motor vehicles. For each consuming country (say, the U. S.), trade is represented as the fraction of the country's total material consumption that comes from each world producing region (e.g., Canada, Mexico, and Japan). For each country/producer pair (e.g., Japan to the U. S.), the LEM also represents the fraction of transport that occurs by ship, and the shipping distance. Appendix B documents the analysis of international trade in materials.

In the LEM, the parameters in the materials or vehicle lifecycle that vary from producing country to producing country are:

i) the source of materials or vehicles (the contribution of each producing region to the total consumption of the target country (Appendix B)

ii) the energy intensity of production (in BTU/lb; parameter ENR in eq. H.3; discussed in this section)

iii) the mix of fuels used to generate electricity used to assemble motor vehicles (discussed in the section on motor-vehicle assembly, in this appendix)

iv) the mix of fuels used to generate electricity used to produce aluminum (involved in the calculation of the parameter ENEF in eq. H.3; discussed in the section on aluminum, in this appendix)

v) the shipping distance from producing country to consuming country (Appendix B)

All other parameters are fixed at what are nominally U. S. values.

Energy intensity of production. The energy intensity of production in the major non-U.S. material producing regions of the world is represented relative to that estimated for the U. S. (e.g., the BTU/lb. energy intensity of material production in Japan is the same as that in the U .S.). Hence, for any designated consuming country C (recall that the LEM can designate up to 30 different "consuming" or target countries), the parameter ENR in eq. H.3 is equal to the ENR for each *producing* country PC (including C as its own producer) multiplied by the contribution of country PC to the total material consumption of C, summed over all producing countries. Formally:

$$\sum_{L} ENR_{F,M,L} = \sum_{PC} \left[MC_{PC,C,M} \cdot ENRR_{PC,US,M} \cdot \sum_{L} ENR_{F,M,L,US} \right] \qquad \text{eq. H.6}$$

where:

$ENR_{F,M,L}$ and subscripts M,L, and F are defined above

$ENR_{F,M,L,US}$ = the energy-usage rate *in the U. S.* (BTUs/lb.; see Table H-6 for results results aggregated over all stages of the lifecycle, for the U. S)

$MC_{PC, C,M}$ = the contribution of producing country PC to the total consumption of material M in consuming country C (see Appendix B.)

$ENRR_{PC, US, M}$ = the energy-usage rate in producing country PC relative to that in the U. S., for producing material M (discussed below)

subscript PC = major material producing countries (see Appendix B; the consuming country designated for analysis is included as its own producer)

subscript C = consuming country designated for analysis

This also applies to motor vehicle production (assembly), as well as to materials production. The case of motor-vehicle assembly is discussed below.

In the estimation of the relative energy requirements (ENRR) in other material-producing countries, the following informaton was useful:

• APERC (2002) reports that energy consumption per tonne of steel in China "will likely fall from 44 PJ in 1995 to 35 PJ in 2010, which is a little higher than the level in industrialized countries in the 1970s" (p. 20). However, data in another reporty by APERC (2001) indicate that by 1998 the energ intensity of steel production in China had fallen to about the level of that in the U. S.

• The USGS (2001) reports that Russia's aluminum industry badly needs to modernize, and in particular needs to improve its energy efficiency.

Given this, I assume that the energy intensity of production relative to that in the U. S. is as follows, for all materials:

-- Canada, Northern Europe, Southern Europe, Japan, Germany, Korea: same;

-- Former Soviet Union: 20% higher;

-- Asian exporters and other: 10% higher.

Aggregating over the lifecycle

In eqs. H.2 to H.6 emissions (EPR), energy use (ENR), and other-input use (OIR) are summed over all stages of the lifecycle of the material. To do such a summation – to be able to add emissions per unit from stage L to emissions per unit fom stage L+1, the "unit" of "emissions per unit" must be the same for each stage. In all cases – for all parameters and all stages – I have expressed emissions, energy use, and input use relative to lb. of finished material output. In this way, emissions, energy use, or input use or one stage can be added to that from another stage. (If emissions, energy use, or input use were expressed relative to the output of each stage, then estimates for one stage could not be added to estimates for another, because the units of output of each stage are different.)

However, in most cases, the original input-output and emissions data are expressed for each stage, as emissions, energy use, or other inputs to stage L per unit of output from stage L, *not* per unit of finished material M produced. These data have to be converted from inputs per unit of output of stage L to inputs per lb. of finished

material output. To do this, we must know the relationship between the output of stage L and the production of a lb. of finished material. This relationship is represented by compounding (multplying) the I/O ratios from stage L to finished product. This compounding is done for the inputs for each stage L. Formally:

$$ENR_{F,M,L} = ENR^*_{F,L,M} \cdot IO_{L+1} \cdot IO_{L+2} \cdot IO_{L+3} \cdot \ldots \qquad \text{eq. H.7}$$

where:

$ENR_{F,M,L}$ = energy-usage rate: BTUs of fuel F input at stage L of the lifecycle of material M, per lb. of finished material M produced

$ENR^*_{F,M,L}$ = energy-usage rate: BTUs of fuel F input at stage L of the lifecycle of material M, per unit of output of stage L (note that this is per unit of output from stage L, whereas $ENR_{F,M,L}$ is per lb. of output of finished material M)

$IO_{S+i.}$ = input from stage L per unit of output of stage L+1

For example, in the case of steel production, we have the following relationships:

1.4 tons of coal --> 1.0 tons of coke	(L --> L+1)
0.53 tons of coke --> 1.0 tons of pig iron	(L+1 --> L+2)
0.83 tons of pig iron -- > 1.0 tons of raw steel	(L+2 --> L+3)
1.22 tons raw steel --> 1.0 tons steel sheet	(L+3 --> L+4)
1.40 tons steel sheet --> 1.0 tons steel parts	(L+4 --> L+5)

Given these relationships, I determine the amount of coal required to produce 1.0 ton of raw steel as follows: 1.40 x 0.53 x 0.83 x 1.22 x 1.40 = 1.05 tons. Note that this tells us the amount of coal input to stage L per unit of product output from the lifecycle. If coal is input to any other stages, the same calculation is done starting from that stage. The total coal input is then the sum of all inputs for each stage, expressed per unit of output from the lifecycle (eq. H.3). An analogous calculation is done for OIR and EPR.

Of course, for the last stage of any lifecycle, or in cases in which the whole lifecycle is characterized as a single stage, ENR = ENR*.

Treatment of manufacturing ("pre-consumer," or "home")scrap

Eq. H.2, which shows the components of the grand-total emissions from the production of 1.0 lbs. of a material, has a term called "scrap recycling credit," (SRC). This credit is the eduction in emissions of pollutant P from the lifecycle of material M due to the use of manufactured scrap instead of raw materials. We discuss this term in this section.

In the process of manufacturing automotive parts, there often is a sizable amount of leftover material, called "home" scrap. For example, the manufacture of one ton of aluminum automotive parts can produce up to 1.9 tons of home scrape (ANL et al.,

1998). Steel stamping also produces a significant amount of manufactured scrap (ANL et al., 1998).

This pre-consumer clean scrap can be recycled into new products with very little presorting or processing. Usually, recycling clean materials into finished products is less energy-intensive than creating finished products from raw materials. As a result, the way scrap from the manufacturing process is treated in the calculations has a large effect on the embodied energy and emissions values for many materials. In principle, the correct way to treat scrap is as an integral part of a world model of the supply and demand of materials and substitutes. This model would be run once in some baseline configuration, and then again with changes that represent the effect of a specific policy that affected motor-vehicle manufacturing. The differences between the two cases in the supply and demand for materials would be attributable to the motor-vehicle policy. An engineering lifecycle model then would estimate the energy and emissions impacts of the equilibrium supply and demand changes.

Unfortunately, we are not able to model the world in this conceptually correct manner. Instead, in this section, we develop an analytical expression that shows the impact of always recycling some fraction F of the available manufacturing scrap S ("Always recycling" means that clean scrap is assumed to be recycled directly to finished product, through an infinite number of iterations -- the first round of scrap is recycled into finished product and a second-round of scrap; the second round of scrap is recycled into finished product and a third round of scrap; the third round of scrap is recycled, and so on -- until all of the original clean scrap is made into finished product.) This expression includes a single parameter that is meant to account (quite simplistically) for the effects that ideally would be handled in a world model of supply and demand.

Specifically, what we develop an expresson for a "scrap recycling credit," paramter SRC in eq. H.2. The key assumptions underlying the development of this expression are:

i) the manufacturing process produces S lbs. of scrap for every 1.0 lb. of finished product;

ii) some fraction F of the available manufacturing scrap S is recycled to finished products;

iii) some fraction D of the recycled manufacturing scrap FS actually displaces production of finished material from virgin (raw) materials (the rest, D minus1, goes to satisfy net new demand for the finished material).

The parameters S, F, and D vary from material to material. With these assumptions, the scrap recycling credit (SRC) will be estimated as the difference between:

a) the present value of the stream of emissions associated with infinitely recycling a given amount of material to finished product; and

b) the present value of the stream of emssions associated with making from raw materials the amount of finished product actually displaced by the output of finished product from recycling.

The present value of the stream of emissions is a function of emissions from each "cycle" and a discount rate. Emissions from each cycle can be estimated from eqs. H.2 to H.6. We express the results per lb. of finished product output from the scrap recycling process (because the units of SRC are g/lb-finished-M; eq. H.2).

Formally (and omitting most subsripts M and P for ease of exposition):

$$SRC = \frac{E2^* - E1^*}{Q^*} \qquad \text{eq. H.8}$$

$$E2^* = f(E2, F, S, rp)$$

$$E1^* = f(E1, F, S, D_{MS}, rp) \qquad \text{eqs. H.9, H.10, H.11}$$

$$Q^* = f(F, S, rp)$$

$$E1 = EEN_{MV} + EOI_{MV} + EPR_{MV}$$

$$E2 = E2\hat{} \cdot K1$$

$$E2\hat{} = EEN_{MR} + EOI_{MR} + EPR_{MR} \qquad \text{eqs. H.12, H.13, H.14, H.15}$$

$$rp = \frac{r}{P}$$

where:

SRC = the scrap recycling credit, in g-emissions/lb.-finished-product (in eq. H.2)

E2* = the present value of the series of lifecycle emissions associated with infinitely recycling some fraction F of the available manufacturing scrap S to finished product (g)

E1* = present value of the series of lifecycle emissions associated with making from raw materials the amount of finished product that is displaced by the output of recycling manufacturing scrap (g)

Q* = the present value of the stream of finished-product output from the recycling of manufacturing scrap (lbs.)

D = the fraction of the recycling output that in the final economic equilibrium actually displaces production of finished product from virgin (raw) material (discussed below)

E1 = lifecycle emissions from producing 1.0 lb. of finished material M and S lbs. of clean scrap from raw materials (does not include transportation of finished materials to end users)

E2 = lifecycle emissions from producing 1.0 lb. of finished material M from recycling manufacturing scrap

E2^ = lifecycle emissions from producing 1.0 lb. of finished material M from recycling post-consumer material (does not include transportation of finished materials to end users)

K1 = energy use and emissions from recycling manufacturing scrap relative to energy use and emissions from recycling post-consumer material (assumed to be 0.90; discussed briefly below)

EEN, EOI, and EPR as defined above (eqs. H.2 to H.6)

S = lbs. of clean (manufactured or "home") scrap produced per 1.0 lb. of finished product produced from raw materials

F = fraction of S that is recycled to finished products

rp = the periodic discount rate, where the period in question is that from one recycle/production cycle to the next.

r = the annual discount rate (assumed to be a function of time; see the discussion in Appendix D)

P = periods per year, where the period in question is that from one recycle/production cycle to the next (assumed to be 4/year (3-month cycles) in the base case)

subscript MV = finished product M produced from virgin materials

subscript MR = finished product M produced from recycling post-consumer products

subscript MS = manufacturing scrap

Note that here we distinguish recycling post-consumer material (parameter E2^) from recycling manufacturing scrap (parameter E2), and estimate the latter relative to the former. We do this because there are minor differences between recycling manufacturing scrap and recycling post-consumer material, and the available estimates of secondary or "recycling" energy appear to apply to post-consumer material. Presumably it takes slightly less energy and produces less emissions to recycle manufacturing scrap than to recycle post-consumer material, because the former is cleaner, more homogenous, and perhaps closer to recycling centers. We assume 10%; therefore the parameter K1 above is 90% or 0.90.

The parameter D, which we will call the net displacement fraction, is meant ultimately to capture the effects of additional output on price and ultimately demand. In principle, additional production of finished product from recycling manufactured scrap will reduce the price of and hence increase the demand for finished product. The additional or "new" demand spurred by the lower price does not by definition displace anything; hence, to the extent that recycling spurs additional demand, there is no scrap recycling credit in the form of displaced production and emissions. The scrap recycling credit obtains only for the fraction of the recycled-product-output that actually displaces "old" or "original" demand, which we assume was met by production from

raw materals. This fraction is given by the parameter D. Ideally, this fraction would be estimated by a economic equilibrium model of supply and demand for virgin materials, recycled materials, and substitutes. Since we are unable to do this here, we just assume values for D directly[2]. (See the main report for a bit more discussion.)

Given that F, S, D, r and P are input parameters, and EEN, EOL, and EPR are defined by eqs. H.2 to H.6, what remains is to develop E1*, E2*, and Q* as a function of E1, E2, F, S, r, and P. We develop these expression as follows. Recall that our objective is to estimate the present value of the series of emissions associated with producing finished product from recycling scrap, and the present value of the series of emissions associated with producing the same amount of finished product from raw materials. The series of emissions to be modeled consists of the emissions associated with the initial (zeroeth cycle of) production, the emissions associated with the product from the first cycle of recycling, the emissions associated with the product from the second cycle of recycling, and so on.. We discount each emissions "cycle" after the first to the time of the initial (zeroeth) emission, so that all cycles of the stream may be properly added together.

Now, we have defined E1 to be the lifecycle emissions from producing 1.0 lbs of finished product from raw materials, and E2 to be lifecycle emissions from producuing 1.0 lbs of finished product from recycling. Hence, we know that in general $E1 \cdot Q_T$ or $E2 \cdot Q_T$ emissions result from the production of Q_T lbs. of finished material in cycle T. Hence, our task now becomes to estimate the amount of finished product Q_T produced at each cycle in the series.

Assume that material production, whether from recycled scrap or raw materials, always produces S lbs. of scrap for every 1.0 lb. of finished production. Assume further that in the recycing case, some fraction F of the S lbs. of scrap is recycled, at every cycle or step. Now, we must start the system with production from raw materials. This results, by definition, in 1.0 lb. of finished material, S lbs. of scrap, $F \cdot S$ lbs. of scrap recycled, $(1-F) \cdot S$ lbs. of scrap discarded (and of no further consequence in our emissions analysis), and E1 grams of emissions. Thus far, then, we have E1 emissions and 1.0 lbs. of finished product. However, $F \cdot S$ lbs. of scrap are recycled. Assuming that recycling always produces finished product and scrap in the ratio of 1:S, then the finished production output fraction is always 1/(1+S), and the scrap output fraction is always S/(1+S). Thus, from the $F \cdot S$ lbs. of recycled scrap we get $F \cdot S/(1+S)$ lbs. of finished product and $F \cdot S \cdot S/(1+S)$ lbs. of scrap, of which the fraction F or $(F \cdot S)^2/(1+S)$ is recycled. We thus have the following outputs of finished product and recycled scrap, step by step (ignoring now discarded scrap, which is of no consequence in our analysis, and for the moment not discounting):

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[2] In a closed system in which there is no change in demand for the material in question, no substitutes for the material in question, and no change in recycling of the material in question other than the one being analyzed, D = 1.0.

	Finished product	*scrap*	*recycled scrap*
zeroeth cycle	1	S	FS
first cycle	$F \cdot S \cdot \frac{1}{1+S} = \frac{F \cdot S}{1+S}$	$F \cdot S \cdot \frac{S}{1+S} = \frac{F \cdot S}{1+S} \cdot S$	$= F \cdot \frac{F \cdot S}{1+S} \cdot S = \frac{(F \cdot S)^2}{1+S}$
second cycle	$\frac{(F \cdot S)^2}{1+S} \cdot \frac{1}{1+S} = \left(\frac{F \cdot S}{1+S}\right)^2$	$\frac{(F \cdot S)^2}{1+S} \cdot \frac{S}{1+S} = \left(\frac{F \cdot S}{1+S}\right)^2 \cdot S$	$F \cdot \left(\frac{F \cdot S}{1+S}\right)^2 \cdot S = \frac{(F \cdot S)^3}{(1+S)^2}$
third cycle	$\frac{(F \cdot S)^3}{(1+S)^2} \cdot \frac{1}{1+S} = \left(\frac{F \cdot S}{1+S}\right)^3$	$\frac{(F \cdot S)^3}{(1+S)^2} \cdot \frac{S}{1+S} = \left(\frac{F \cdot S}{1+S}\right)^3 \cdot S$	$F \cdot \left(\frac{F \cdot S}{1+S}\right)^3 \cdot S = \frac{(F \cdot S)^4}{(1+S)^3}$
fourth cycle	$\frac{(F \cdot S)^4}{(1+S)^3} \cdot \frac{1}{1+S} = \left(\frac{F \cdot S}{1+S}\right)^4$	etc.	etc.

Equation series H.16

Now, the finished-product output of each cycle is discounted to present value (to the zeroeth cycle) by dividing by $(1+rp)^T$ where T is the number of the cycle. Hence, the discounted output of finished product is as shown in the table below. The amount of virgin product displaced by the finished product output is just the finished product output multiplied by the parameter D. Thus:

	Finished product output of recycling	*Virgin product displaced*
zeroeth cycle	1	1
first cycle	$\frac{F \cdot S}{(1+S) \cdot (1+rp)}$	$D \cdot \frac{F \cdot S}{(1+S) \cdot (1+rp)}$
second cycle	$\left(\frac{F \cdot S}{(1+S) \cdot (1+rp)}\right)^2$	$D \cdot \left(\frac{F \cdot S}{(1+S) \cdot (1+rp)}\right)^2$
third cycle	$\left(\frac{F \cdot S}{(1+S) \cdot (1+rp)}\right)^3$	$D \cdot \left(\frac{F \cdot S}{(1+S) \cdot (1+rp)}\right)^3$
fourth cycle	$\left(\frac{F \cdot S}{(1+S) \cdot (1+rp)}\right)^4$	$D \cdot \left(\frac{F \cdot S}{(1+S) \cdot (1+rp)}\right)^4$

Displacement is not relevant in the zeroeth cycle because this cycle is assumed to *start* with raw (virgin) materials.

If we designate the quantity $\frac{F \cdot S}{(1+S)\cdot(1+rp)}$ as Q′, then w′e see that the present value of the output of finished product is 1 (zeroeth cycle) + Q (first cycle) + Q'^2 + (second cycle) + Q'^3 (third cycle) + Q'^4 (fourth cycle) + ...Thus, we now have an expression for Q* (eq. H.8), the present value of the stream of finished-product output of recycling[3]:

$$Q^* = 1 + Q' + Q'^2 + Q'^3 + Q'^4 + \ldots \qquad \text{eq. H.17}$$

where $Q' \equiv \frac{F \cdot S}{(1+S)\cdot(1+rp)}$ eq. H.18

We now need to estimate the present value of the stream of emissons from indefinite virgin production (E1* in eq. H.8) or infinite recycling (E2* in eq. H.8). As mentioned above, since E1 and E2 are given in g/lb.-finished-product, the present value of the total emssions in grams (E1* and E2*) are equal just the sum of series $E1 \cdot Q_T/(1+rp)^T$ and $E2 \cdot Q_T/(1+rp)^T$, where Q_T are the undiscounted output of finished product from each cycle. The table immediately above, shows the values of $Q_T/(1+rp)^T$ at each cycle. Thus, for E1* we have:

$$E1^* = E1 + E1 \cdot D \cdot \frac{F \cdot S}{(1+S)\cdot(1+rp)} + E1 \cdot D \cdot \left(\frac{F \cdot S}{(1+S)\cdot(1+rp)}\right)^2 + E1 \cdot D \cdot \left(\frac{F \cdot S}{(1+S)\cdot(1+rp)}\right)^3$$

$$+ E1 \cdot D \cdot \left(\frac{F \cdot S}{(1+S)\cdot(1+rp)}\right)^4 + \ldots$$

$$= E1 + E1 \cdot D \cdot Q' + E1 \cdot D \cdot Q'^2 + E1 \cdot D \cdot Q'^3 + E1 \cdot D \cdot Q'^4 + \ldots$$

$$= E1 + E1 \cdot D \cdot Q' \cdot (1 + Q' + Q'^2 + Q'^3 + \ldots)$$

$$= E1 + E1 \cdot D \cdot Q' \cdot Q^*$$

eq. H.19

In the case of E2*, we must first remember that the E1 emissons (those from virgin production) are associated with the 1.0 unit of output from the zeroeth cycle, because the zeroeth cycle involves production from raw (virgin) materials. The

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[3] Although it will turn out that we do not need to simplify this, we can do so anyway, since the infinite series is the binomial expansion of 1/(1-Q′). Hence: $Q2^* = \frac{1}{1-Q'}$

subsequent cycles of scrap production involve emissions from the scrap lifecycle, E2. Hence:

$$E2^* = E1 \cdot 1 + E2 \cdot \frac{\frac{F \cdot S}{1+S}}{1+ip} + E2 \cdot \frac{\left(\frac{F \cdot S}{1+S}\right)^2}{(1+rp)^2} + E2 \cdot \frac{\left(\frac{F \cdot S}{1+S}\right)^3}{(1+rp)^3} + E2 \cdot \frac{\left(\frac{F \cdot S}{1+S}\right)^4}{(1+rp)^4} + \ldots$$

$$= E1 + E2 \cdot Q' \cdot \left(1 + Q' + Q'^2 + Q'^3 + \ldots\right) \qquad \text{eq. H.20}$$

$$= E1 + E2 \cdot Q' \cdot Q^*$$

With expressions for E1*, E2*, and Q*, we can now expand the expression for the scrap recycling credit, SRC, in eq. H.8:

$$SRC = \frac{E2^* - E1^*}{Q^*} = \frac{E1 + E2 \cdot Q' \cdot Q^* - E1 \cdot -E1 \cdot D \cdot Q' \cdot Q^*}{Q^*}$$

$$= \frac{(E2 - E1 \cdot D) \cdot Q' \cdot Q^*}{Q^*} \qquad \text{eq. H.21}$$

$$= (E2 - E1 \cdot D) \cdot Q'$$

This simple formula is an exact analytical expression for the present value of the difference in emissions between infinitely recycling some fraction F of the available scrap S and producing the same amount of finished product from raw material. Substituting the complete expressions for Q′, E1, E2, and rp gives us the expression for SRC as it is implemented in the LEM:

$$SRC = \left(\left(EEN_{MR} + EOI_{MR} + EPR_{MR}\right) \cdot K1 - \left(EEN_{MV} + EOI_{MV} + EPR_{MV}\right) \cdot D_{MS}\right) \cdot \frac{F \cdot S}{(1+S) \cdot (1 + r/P)}$$

eq. H.22

If F or S = 0, the scrap recycling credit is zero, which is appropriate. If the discount rate is zero, the scrap recycling credit is the difference between secondary-production (recycling) emissions primary-production emissions weighted by the fraction of recycled scrap fraction of total output, which is intuitively reasonable. Note that unless the discount rate is relatively high (e.g., greater than 6%/yr.) and the recycling period relatively long (greater than 6 months), the effect of discounting is minor. Even given 6%/yr. and 6-month cycles, discounting reduces SRC by only 3% relative to not discounting at all. With the baseline parameter values (2%/yr., 4 periods/yr.) discounting reduces SRC by less than 1%.

Treatment of recycling post-consumer scrap

<<NOTE: the following section describes the current representation in the LEM of recyling post-consuumer scrap. However, this may be revised, along the lines of the partial discussion a few paragraphs below>>

Eq. H.2, which shows the components of the grand-total emissions from the production of 1.0 lbs. of a material, has a term called "end-of-life recycling credit," (EOLRC). This credit is the reduction in emissions of pollutant P from the lifecycle of material M due to the use of recycled post-consumer material instead of raw materials. We discuss this term in this section[4].

To model the environmental impact of the fate material at the end of its life in the original product, we address two issues: i) the fraction of the material that is recycled rather than landfilled, and ii) how a marginal change in the supply of recycled material affects the overall balance between primary (virgin) and secondary (recycled) production. The second issue also can be understood as the extent to which recycled automotive material displaces other recycled material rather than virgin material. We incorprate these issues into the following simple formulation:

$$EOLRC_M = -\left(ERML^*_{M,V} - ERML^*_{M,R}\right) \cdot NDF_{M,R} \cdot EOLRF_M \cdot DF_M \qquad \text{eq. H.23}$$

$$ERML^*_M = EEN_M + EOI_M + EDC_M \qquad \text{eq. H.24}$$

$$DF_M = \frac{1}{(1+r)^{VL_M}} \qquad \text{eq. H.25}$$

where:

subscript M,V = primary (virgin) production of material M
subscript M,R = secondary (recycled) production of material M
$EOLRC_{M,P,}$ = the "end-of-life recycling credit": the reduction in emissions of pollutant P from the lifecycle of material M due to the use of recycled post-consumer material instead of virgin raw materials (grams-P/lb.-finished-M)

[4] A related issue is the extent to which products such as automobiles comprise recycled material. Ideally, the usage of recycled material in products such as automobiles would be represented in a economic model, in which an incremental increase in demand for material X is met by a combination of increased recycling of X and virgin production of X in accordance with the relative costs and qualities of recycled versus virgin materials. I do not undertake such an economic analysis here. Instead, I make simple assumptions about the percentage of materials in cars that comes from recycling plants rather than virgin-ore-processing plants (Table H-3). These assumptions are based partly on the information discussed below in the sections on individual materials.

ERML, EEN, EOI, and EDC are defined above (see eqs. H.1, H.2)

DF_M = the discount factor for material M

r = the discount rate used to discount the value of future energy savings to a present value (assumed to be a function of time; see the discussion in Appendix D)

VL_M = the product life of material M (years; in the LEM, vehicle life is calculated from a formula relating age to mileage, given an assumption about total lifetime mileage, and varies by fuel type and drivetrain type [see the main documentation for details]; however, for simplicity we assume here that all products have a 10-year life)

$EOLRF_M$ = the fraction of material M that is recycled, at the end of life of the vehicle (Table H-6; it appears that most aluminum, steel, lead, and copper is recycled at the end of its life [Das, 2000; Young and Vanderburg, 1994; Stodolsky et al., 1995])

$NDF_{M,R}$ = the net displacement of virgin material by recycled material M: of the total amount of recycled material, the fraction that on balance (in the final economic equilibrium) displaces virgin production (I simply assume 50% for all materials)

With this method, I calculate an emissions-reduction "credit" for displaced virgin production, based on the present value of the difference between primary and secondary production at the end of life of the vehicle.

The logic behind this method is as follows. The amount of virgin production displaced per unit of material that reaches the end of its life is the product of the fraction of end-of-life material that is recycled (EOLRF) multiplied by the fraction of recycled material that displaces virgin production (NDF). The emissions savings of displacing virgin material production is equal to the emissions associated with virgin production less the emissions associated with recycling itself (secondary production).

The end-of-life recycling credit is applied to all materials, whether from virgin production or recycled materials. In some cases, the credit may be larger than the energy requirements of secondary production from recycled materials. This in itself is not illogical or otherwise problematic. What *could* be problematic is assuming that the amount of virgin material displaced by material recycled from a particular product (the multiplication of NDF and EOLRF) is greater than the amount of virgin material assumed to be in the product in question (shown in Table H-3 in the case of motor vehicles.) While this could hold for the use of a material in any one product, it cannot hold in the equilibrium for all uses of the material. (That is, it cannot be true that recycling is displacing more virgin production than is going in to all products, because the maximum amount of virgin production that can be displaced is the amount in all products.)

<<The preceding treatment may be revised, along the lines of the following:>>

A closely related analytical issue is the recycling of post-consumer scrap (PCS). The theoretically correct way to treat PCS is the same as the theoretically correct way to treat manufacturing scrap: as an integral part of a world model of the supply and demand of materials and substitutes, taking into account the costs and output quality of recycling as well as the costs of virgin production. Given that the LEM cannot yet do this, I adopt here the method developed above for recycling of manufacturing scrap. This method produces an exact analytical expression for the emissions impacts of displacing virgin production by infinite recycling of some PCS. (Infinite recycling means that after "starting" with production from virgin materials, some fraction of the PCS from this virgin production is recycled to finished products; then the same fraction of the PCS from the recycled finished product is recycled to finished products, and so on, indefinitely.) The method also includes a single parameter (D_{MS} in eq. H.22) that is meant to account for the economic effects that ideally would be handled in an equilibrium model of supply, demand, and prices.

Four obvious adjustments and one subtle adjustment to eq. H.22 result in an equation used to calculate the scrap recycling credit (SRC) for PCS:

1) The parameter K1, which converts emissions from the recycling of PCS to emissions from the recycling of manufacturing scrap, is eliminated, because in this case of course we want emissions from the recycling of PCS.

2) The parameter D_{MS} becomes the D_{PCS}, the fraction of the output of the PCS recycling plant that in the final economic equilibrium actually displaces production of finished product from virgin (raw) material.

3) The parameter S, units of manufacturing scrap generated per unit of finished-product output, is redefined to be units of PCS per unit of finished-product output, and is equal to 1.0, because *every* unit of product eventually becomes post-consumer scrap, and there can be no more PCS than there is original finished product.

4) The parameter F, the fraction of manufacturing scrap that is recycled, is redefined to be the fraction of PCS that is recycled, and is designated EOL (end-of-life recycling fraction).

5) The timing of the recycling is slightly different from that in the case of manufacturing scrap.

Treatment of "co-products" of materials lifecycles

Some materials production processes produce significant amounts of byproducts, also called "coproducts". For example, the copper lifecycle produces large quantities of sulfuric acid, and the steel lifecycle produces coke oven and blast furnace gas, which can be fuels (ANL et al., 1998). The best way to incorporate the energy and emissions impacts of coproducts in a lifecycle analysis is to model the effect of new coproducts on the global market for coproducts and their substitutes. However, we are unable to do this. Instead, we make a crude, direct estimate of the net amount of original (e.g., sulfuric acid) production that is displaced by the availability of coproduct (sulfuric acid from the copper lifecycle). Then, the emissions foregone from the original

(sulfuric acid) production displaced by the coproduct are subtracted from the lifecycle emissions estimated for the material in question (e.g., copper). In essence, we assign to the coproduct an energy-use and emissions displacement "credit".

As discussed in the main documentation report, a unit of coproduct (sulfuric acid from the copper lifecycle) will not displace exactly one unit of (sulfuric acid) production elsewhere, because the availability of low-cost (sulfuric acid) coproduct will reduce the price of and hence increase the demand for product (sulfuric acid). Thus, in effect, only some of the co-product will displace original production – some of it will go to satisfy new demand spurred by the lower price. (Moreover, in some cases, some of the coproduct might not be marketed, perhaps because of a lack of a distribution infrastructure.) In the main report, I estimate a parameter, the "net displacement fraction" (NDF), that represents the fraction of co-product output that in the final equilibrium goes to displace original production rather than to satisfy new demand. Given this parameter, the final "emissions displacement credit" associated with a unit of coproduct C is equal simply to the emissions from alternative means of producing a unit of C multiplied by the fraction of coproduct marketed and by NDF.

Formally:

$$EDC_{M,C} = -CPR_{M,C} \cdot CPMF \cdot NDF_C \cdot NLCE_C \qquad \text{eq. H.27}$$

where:

EDC = energy or emissions displacement credit for producing coproduct C in the lifecycle of M (g/lb.-M or BTU/lb.-M) (in eq. H.2)
$CPR_{M,C}$ = the coproduct production rate (lbs.-C/lb.-M; discussed below)
$CPFM_C$ = the fraction of coproduct that is actually marketed, rather than discarded (discussed below)
NDF_C = net displacement factor in the market for C (unitless; can range from close to 0, in the case in which demand is relatively elastic, to close to 1, in the case in which demand is relatively inelastic; see the main report for more details)
$NLCE_C$ = net lifecycle emissions or energy use for coproduct C (g/lb.-C or BTU/lb.-C) (discussed below)

The LEM currently considers sulfuric acid coproduct from the copper lifecycle, and coke oven gas and blast furnace gas from the steel lifecycle. Our assumptions regarding the parameters in eq. H.27 are as follows:

Material -->	**copper**	**steel**	**steel**
Coproduct -->	*sulfuric acid*	*coke oven gas*	*blast fur. gas*
Coproduct rate (CPR): units coproduct/lb.	2.30 (Table H-23)	0.0030 (Table H-12; output gas less input gas, per lb.	0.0033 (Table H-12; output gas less input gas, per lb.

material		steel output)	steel output)
Fraction of coproduct marketed (CPFM)	0.90 (assume easy to get to market)	0.50 (assume some cannot be marketed and so is flared)	0.50 (assume some cannot be marketed and so is flared)
Units displaced per unit coproduct (NDF)	0.50 (assume demand for coproduct is moderately elastic)	0.75 (assume demand or coproduct is relatively inelastic)	0.75 (assume demand or coproduct is relatively inelastic)
Coproduct units	lb.	10^6 BTU	10^6 BTU
Product or activity displaced	sulfuric acid	natural gas used in industrial boiler	natural gas used in industrial boiler

Note that in the case of coke oven gas and blast furnace gas in the lifecycle of steel, a small amount of the gas also is *input* to the steel lifecycle ANL et al, 1998). I assume of course that the output gas is used first to fulfill input requirements, with any leftover then being flared (if there is no market for the gas) or marketed to displace natural gas used in industrial boilers.

These assumptions reduce lifecycle emissions by less than 10%.

A note on data quality

The estimates in this report combine data of varying quality from diverse sources. Due to the proprietary nature of much of the necessary data for life cycle inventories such as this one, it is difficult for researchers outside of industry to obtain reliable current data. The available data are usually in aggregated form and often it is unclear exactly which processes are included in the calculations.

For certain materials, there is substantial variation among energy and emissions estimates from different sources. This could be due to differences in source data, i.e. current vs. older data, site-specific vs. national average data, etc. More likely, it is due to differences in process inclusion and exclusion from the final published values. Unfortunately, I do not know the origin of the discrepancies and do not have access to the original disaggregate data. I note significant discrepancies.

Further research

Good quality public data on energy consumed in common industrial processes and emissions produced by those processes are not available for most materials. Since only public data sources were used to complete this section, and most available public data sources do not publish all of the relevant background data, the information found here is of uncertain quality. More complete studies of this type are an important topic for future research as supporting information for life cycle analyses of not only automobiles, but of all end products that use basic materials.

MATERIALS IN VEHICLES

Materials in conventional vehicles, excluding fuels and lubricants

In the first version of the Lifecycle Emissions Model (LEM) (DeLuchi, 1993), I estimated the materials content of automobiles on the basis of data from what formerly was called the Motor Vehicle Manufacturer's Association. I assumed that electric vehicles had the same materials content (excluding batteries) as conventional internal-combustion-engine vehicles. The estimation of the materials content now has been completely overhauled.

The LEM now calculates the materials composition of the baseline light-duty vehicle (LDV) as a function of the city-cycle fuel economy. On the basis of the analysis of Greene and Duleep (1998), I assume that as vehicles become lighter and more fuel efficient they have more aluminum and plastic/composites and less steel. Table H-3 shows the assumptions.

The LEM calculates the materials composition for any input city cycle fuel economy by interpolating between the pertinent points in table above.

Materials in electric vehicles, excluding batteries

In the original version of the LEM, electric vehicles *sans* batteries had the same materials composition as conventional internal-combustion-engine vehicles (ICEVs). Recently, the EVTECA project (ANL et al., 1998) has estimated the materials content of EVs *sans* batteries and ICEVs in detail. On the basis of the EVTECA data, I assume the following ratios of EV materials percentage to ICEV materials percentage:

Plain carbon steel	1.08
High strength steel	0.85
Stainless steel	0.80
Recycled steel	1.00
Iron	0.50
Advanced composites	1.18
Other plastics	1.08
Fluids and lubricants	0.00
Rubber	1.12
Virgin aluminum	0.85
Recycled aluminum	difference
Glass	1.12
Copper	2.00
Zinc die castings	1.00
Powdered metal components	0.60

Other materials (Lead)	1.10

These factors apply to light-duty battery electric vehicles excluding batteries, and light-duty fuel-cell electric vehicles excluding batteries, fuel cells, or fuel-storage systems. They do not apply to heavy-duty fuel-cell vehicles, which I assume have the same composition as heavy-duty ICEVs, excluding the fuel-cell, battery, and fuel-storage system.

Materials in electric-vehicle batteries

The model now has materials breakdowns for advanced lead/acid (Pb/acid), nickel-metal/hydride (NiMH), and lithium/polymer (Li-polymer) batteries. (The original model had a breakdown for a sodium/sulfur battery only.) The breakdowns are shown in Table H-4.

I estimate a fleet-average mix of battery types, for each new model year vehicle from 1970 to 2050. I assume that Pb/acid batteries are introduced first, and dominate the market until around the 2000 model year, after which NiMH come into the market. A few years later, the share of NiMH peaks, and then declines, as Li-polymer batteries begin to capture the market. Table H-5 shows the assumed distribution of the total mass of new battery production across the three different battery types, in each model year. These shares are used to calculate composite or weighted-average emissions from battery production in a target year.

Along with the new battery types, four new battery materials were added to the model: sulfuric acid, potassium hydroxide, nickel, and lithium.

On the assumption that many of the materials used in batteries are more "refined" than are the "generic" materials for which we have data on energy-production intensity, and allowing for the complexity of battery manufacture, I have multiplied the total energy/lb requirements of battery material manufacture and assembly by 1.20.

Note that reasonable variation in the materials breakdown can change CO_2-equivalent emissions by 5.0 g/mi or more. It thus is important to specify the battery composition accurately.

Other notes on materials contents

I changed the material composition of LNG containers slightly, to 65% stainless steel, 25% carbon steel, 5% plastic (of which 2/3 is advanced composites), 3% aluminum, and 2% copper, on the basis of the statements in Powars et al. (1994) that the inner tank of an LNG dewar is stainless steel, the outer tank is stainless or carbon steel, the insulation is aluminized mylar, and the internal supports are stainless steel or fiberglass.

I broke the "plastics" category into "advanced composites" and "other plastics". I assumed that for vehicles and fuel storage tanks, 2/3 of the plastic/composite total is advanced composites. For fuel-cell systems and batteries, I assume that 1/3 of the plastic/composites total is advanced composites.

The composition of CNG tanks now is a function of the model year. On the basis of the analyses in Liss et al. (1998) and Richards et al. (1996), I assume that cylinders first are primarily high-strength steel, then aluminum, then aluminum wrapped with composite fiber, and then plastic wrapped with composite fiber.

ESTIMATION OF ENERGY AND EMISSIONS IN THE MATERIALS LIFECYCLE

Estimates of energy and emissions in the LEM

Table H-6 presents my estimates of the amount and kind of energy required to make a pound of materials in automobiles. In this work, "embodied energy in materials is defined as the energy contained in a fabricated material part, reflecting the energy required to process the material from raw material to finished product"(Das et. al., 1995). The embodied energy values given in Table H-6 include, as much as possible, the energy required to make the materials as well as the energy required to produce the raw feedstocks for the materials. Table H-7 lists the sources for these values. Generally, I have relied heavily on the estimates for the Electric Vehicle Total Energy Cycle Assessment (EVTECA) (Argonne National Laboratory [ANL] et al, 1998),Yoshiki-Gravelsins (1993), and Hudson (1982).

The values in Table H-6 do *not* include the energy required to make the fuel that provided the energy for the process of manufacturing these materials, nor do they include the energy required to transport the materials through the manufacturing cycle, nor do they include any of the energy requirements of building, heating, or maintaining the various facilities where the materials are manufactured. (In the lifecycle emissions model [LEM], materials transport is treated explicitly as a separate step.)

The embodied energy values are "cradle-to-gate" rather than "cradle-to-grave" numbers. That is, they do not include any assumptions about what happens to the materials after the automobile stage of their lives. Table H-7 indicates the sources of the ranges of embodied energy values for each material. The last column of Table H-6 presents some information about the fate of the automotive materials at the end of the automobile's life.

The values shown in Table H-6 are for a base year of 2000. As discussed in the sections on individual materials below, modest improvements in energy efficiency can be expected for most materials. I assume therefore that energy intensity declines by 0.3% per year.

Table H-8 shows the process-area (non-combustion) emission factors that are estimated here and input to the LEM. In addition to the factors shown in Table H-8, I also input HF, CF_4, and C_2F_6 emission factors for the aluminum lifecycle (see notes to Table H-8), and a CO_2 emission factor for the production of cement (see the end of this appendix). To calculate CO_2 equivalents, I multiply the aluminum perfluorocarbon emissions by "global warming potentials" (GWPs) developed by the Intergovernmental Panel on Climate Change (IPCC, 1996) (see Table H-8 here).

Table H-9 shows combustion emission factors estimated here; however, in the LEM I do not input combustion emission factors directly, but rather calculate them for each fuel, assuming that the fuels are used in industrial boilers. The Table H-9 factors shown here are for general reference.

Table H-10 shows fuel energy contents used in the energy and emissions calculations here, and Table H-11 shows the energy embodied in some commodities used in the some of the materials lifecycles. Note that some of the values in Table H-10 are slightly different from the values used in the LEM.

INTEGRATED STEEL (VIRGIN) PRODUCTION

Process description

Virgin steel is produced mainly in large integrated steel plants which cover many acres of land. Steel is made in four basic steps. First, the raw materials must be prepared. This part of the process includes transforming coal into metallurgical coke by baking it in coke ovens, refining limestone to make lime, and creating iron ore pellets out of raw ore. Then, coke, iron ore, and sinter are put into the blast furnace where the iron is separated out of the ore. The coke is both the main fuel used by the blast furnace and the reduction agent to transform iron ore into hot metal. The output of the blast furnace is known as pig iron. This is the most capital- and energy-intensive step in the making of steel. To make pig iron into steel, it is fed into a basic oxygen furnace along with about 25% pre-consumer scrap, lime, and oxygen blown into the furnace. Forming and finishing of steel for automotive applications is done through the casting, hot-rolling, pickling, and cold-rolling processes followed by automotive parts stamping.

Table H-12 shows inputs and outputs and emissions for virgin steel production.

The Future of the integrated steel industry

Integrated steelmaking is a process that has been done for over 150 years. Due to tightening environmental regulations and aging cokemaking facilities, it is predicted that there will be a worldwide shortage of metallurgical coke by 2005 (Steel Technology Roadmap, 1998, p.5) Smaller, older blast furnaces are also predicted to be shut down,

shifting production to the larger furnaces. The high cost of building a blast furnace may prevent new ones from being built altogether in the U. S.. Iron production from existing furnaces will decrease by about 20% by 2015 (Fenton, 1997, p.4). Partially to deal with the problem posed by this shortage, the steel industry is moving to reduce the amount of coke needed to produce a ton of steel in a blast furnace. Coke rates are forecasted to drop from the current 380 kg/ton of hot metal to 295 kg/ton of hot metal (Fenton, 1997, p.4). In addition, the industry is slowly shifting some iron production away from the blast furnace altogether, replacing this technology with the direct reduction process. It is estimated that between 10 and 20% of iron production in the U. S. will be via direct reduction by 2015. Direct reduction of iron ore is done using a natural gas or coal-based reductant, rather than the traditional metallurgical coke (Steel Technology Roadmap, 1998, p.9). Basic oxygen furnaces use an average of 74% pig iron. The projected drop in blast furnace pig iron production is going to be a limitation to the future growth of basic oxygen process steelmaking. Steelmakers are experimenting with new technologies that optimize both the blast furnaces and the basic oxygen furnaces. One major improvement that has been made is the extension of the refractory life to a year or more. Unfortunately, this means that the refractory lining of the furnace outlasts the life of the hoods used for emissions control. As air emissions regulations tighten, this incompatibility will become increasingly problematic.

Garvey believes that the industry will become consolidated by 2006 to the point where only 3 integrated companies and maybe 6 or 7 electric arc furnace minimills will supply most of the steel in the U. S.. Pinkham suggests that a third form of steelmaker may enter and possibly even dominate the market. The first two forms are integrated steel mills that supply virgin steel and minimills that supply more recycled steel. The third form combines the two technologies. Even in this scenario, integrated steel production facilities are projected to supply most of the cold-rolled products that are used to make vehicle panels (Fenton, p.4).

Energy efficiency

Further "… improvements in energy efficiency are anticipated as the industry moves toward 100 percent continuous casting (as opposed to ingot casting), improves yields, and produces stronger and lighter steels." However, "… environmental requirements may offset some of the potential gains in industry energy efficiency" (Margolis, 1996, p.13). Changes in the coke-to-pig iron production ratio will reduce energy requirements for making steel to approximately 26,600 BTU/lb.

Air and water emissions

Air emissions have been a limiting factor for the iron and steel industry[5]. Both coke ovens and sinter plants have been shut down recently, in part due to the difficulty

[5] In the future, greenhouse-gas emissions may become another limiting factor. In response to the Kyoto Protocol and the prospect of mandated reductions in greenhouse-gas emissions, "U. S. steel companies proposed a voluntary plan to reduce emissions by 10% by the year 2010. This would be accomplished gradually through the use of new technology, more effective use of materials, and improvement of

of complying with environmental (particularly air emission) regulations. "Fewer than 10 sinter plants are still in operation, compared with 33 plants in 1982" (Margolis, 1996, p.40).

"A recent regulatory development that significantly affects the iron and steel industry has been the development of uniform water quality standards under the Great Lakes Water Quality Initiative" (Margolis, 1996, p.20). It is not clear what this will mean for the industry other than perhaps raise its effluent control costs.

Uncertainty

Among all the materials covered in this appendix, steel is the one that is most analyzed in the literature. Unfortunately, the many sources of data are not consistent with each other. We rely mainly on data from EVTECA (ANL et al., 1998), because it is such a detailed source of information. However, we do have concerns about some of the estimates from EVTECA. For example, as is discussed in footnote a to Table H-12, the refractories energy value given in EVTECA seems too high. It turns out that this value is so high (about 40% of the total embodied energy of the steel) that altering it could significantly change the total embodied energy of steel.

Data sources for steel production

Information on the production process for integrated steel: Environmental Protection Agency's emission factor handbook AP-42 (EPA, 1995), EVTECA (ANL et al., 1998), Bouman (1988), Margolis (1996).

Material and energy data sources: EVTECA (ANL et al., 1998), Bouman (1988), AISI (1995 and 1996), Margolis (1996), Han (1997), Brown et. al. (1985), Gaines and Singh (1995), Yoshiki-Gravelsins et. al. (1993), Sullivan and Hu (1995), Stodolsky et. al. (1995), Griffiths (1996), Wheeler (1982), Cummings-Saxton (1982).

Air emissions data sources: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995), Margolis (1996), Gaines and Singh (1995) p. 196.

Water emissions data sources: Margolis (1996)[6], Steel Technology Roadmap (1998).

ELECTRIC ARC FURNACE (RECYCLED) STEEL PRODUCTION

Process description

Electric arc furnaces produce mainly recycled steel. That is, scrap metal is a main input to the electric arc furnace. Electric arc furnace steel production is relatively simple. Scrap metal, alloying elements, oxygen, lime, and sometimes pig iron are combined in the electric arc furnace. Three electrodes are lowered into the top of the furnace and the

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efficiency of existing energy-producing processes" (Fenton, 1997, p.1). (The proposal did not specify the baseline with respect to which the 10% reduction would be achieved.)

[6] These numbers are taken from effluent regulations, not real data.

electricity melts the contents into steel. Hot metal is tapped from the bottom of the furnace and the slag rises to the top.

Data in Sullivan et al. (1998), shown in Table H-2, indicate that recycled steel is about 25% of the total steel content (recycled plus virgin) in a vehicle. The LEM includes virgin plain carbon steel, virgin high-strength steel, virgin stainless steel, and recycled plain carbon steel. I assume that most steel in a vehicle is plain carbon steel, and that only plain carbon steel is recycled. Given these categories and assumptions, and the estimates of Sullivan et al. (1998), I assume that 30% of total plain carbon steel (recycled plus virgin) is recycled.

In their LCA of automotive materials, Young and Vanderburg (1994) assume that 90% of automotive steel is recycled. Das (2000) apparently also assumes that 90% of automotive steel is recycled at the end of the the life of vehicles. However, Field and Clark (1994) state that only 75% of the total weight of a vehicle is recycled at the end of its life.

Table H-13 shows inputs and outputs and emissions for recycled steel production.

Future of industry

Electric arc furnace steelmaking is a new process relative to the integrated steelmaking process, and advances in energy efficiency, time efficiency, and material efficiency have been rapid. Three main drivers in the industry are lowering "tap-to-tap" time (time to melt the furnace charge and tap the hot metal), lowering the electricity needed for each heat, and lowering the material consumption of the electrodes (Steltech, 1994, p.7). Significant advances have already been made and future advances may require the increased use of pre-consumer scrap and directly reduced iron.

EAF steel and the automotive industry

Electric arc furnaces are used primarily to produce recycled steel, which is not used in large quantities in automobiles due to its generally lower quality and irregular properties. However, this may change as electric arc furnace steel becomes less distinguishable from virgin steel produced in integrated mills. For example, Fenton (1997) reports that "Ford Motor Co. bought nearly 8000 tons of hot-rolled sheet per month from minimills [electric arc furnaces that often use post-consumer scrap metal] in 1997 with the expectation of increasing purchases to 25000 tons per month by 2000. General Motors may eventually buy from minimills provided the quality of their automotive-grade sheet for exposed applications improves" (p. 4).

Data sources

Information on the production process for EAF steel: EVTECA (ANL et al., 1998), Bouman (1988), Margolis (1996).

Material and energy data sources: EVTECA (ANL et al., 1998), Steltech Ltd. (1994), Bouman (1988), Margolis (1996), Han (1997), Brown et. al. (1985), Stodolsky et. al. (1995), Das et. al. (1995).

Air emissions data sources: EVTECA (ANL et al., 1998), Steltech Ltd. (1994), Margolis (1996).

CAST IRON

Process description

Cast iron is made chiefly from recycled iron and steel. The iron is melted in a furnace and cast in molds to become gray iron castings, the final product. The three types of furnaces most commonly used in the iron foundry industry are cupolas, electric arc, and electric induction furnaces. Cupolas use coke as the main fuel, while the others use electricity. The following tables characterize the cupola furnace process. Characterization of other processes was unavailable.

Table H-14 shows inputs and outputs and emissions for cast iron production.

Data sources

Information on the production process for iron: AP-42 (EPA, 1995), EVTECA (ANL et al., 1998).

Material and energy data sources: EVTECA (ANL et al., 1998), Stodolsky et. al. (1995), Wheeler (1982), Cummings-Saxton (1982), Han (1997), Gaines and Singh (1995), Sullivan and Hu (1995).

Air Emissions data sources: EVTECA (ANL et al., 1998).

PRIMARY (VIRGIN) ALUMINUM

Process description

Primary aluminum is produced via a combination of the Bayer process for bauxite ore preparation and the Hall-Heroult electrolytic cell for smelting. Unlike many other basic metals that are made using a variety of processes, almost all aluminum is made in the same way.

In the Bayer process, bauxite ore is dried, ground in ball mills, and mixed with a preheated solution of sodium hydroxide. Lime is added to improve the solubility of alumina (Al_2O_3). The resulting slurry is pumped through a heated "digester". After 5 hours, the slurry has separated into sodium aluminate and insoluble "red mud" particles. The solution becomes supersaturated with sodium aluminate and crystals of alumina trihydrate are added to cause the alumina to precipitate out of solution. The alumina trihydrate is washed, filtered, and calcined to form crystalling alumina. The red mud is disposed of.

The Hall-Heroult process is an electrolytic reduction reaction that produces aluminum metal. The reduction occurs in shallow rectangular shells of steel lined with carbon called "pots". The anodes are carbon electrodes that extend into the pots and the

carbon lining becomes the cathode. Molten cryolite (Na_3AlF_6) is the electrolyte as well as the solvent for the alumina. Aluminum is deposited at the cathode (the carbon lining) and remains as molten metal below the surface of the cryolite bath. The carbon anodes are continuously depleted by the reaction. Every 1-2 days, the aluminum metal is tapped from the pots and transferred to a furnace where final alloying, purification, and eventually rolling or casting occurs.

The reduction of alumina to aluminum produces substantial emissions of carbon dioxide:

$$Al_2O_3 + 3/2C \text{ --> } 2Al + 3/2CO_2 \qquad \text{eq. H.28}$$

Aluminum production also produces significant emissions of perfloruocarbons (PFCs). These CO_2 and PFC emissions are estimated as process-area emissions in Table H-15.

Table H-15 shows inputs and outputs and emissions for primary (virgin) aluminum production.

The future of the industry

Yoshiki-Gravelsins et. al. (1993) indicate that new aluminum smelters require 92 million BTU of electricity per kg of aluminum produced. Older smelters required approximately 140 million BTU of electricity to produce the same amount of aluminum. Margolis and Eisenhauer (1998) identify inert anode development and implementation as the most critical long-term technical need of the primary aluminum industry. According to them, the time horizon for the development of inert anodes for the reduction of alumina to aluminum is 20 years (p. 27). Currently, anodes are consumed in the aluminum reduction process and must be replaced periodically. Inert anodes would be non-consumable and would increase process efficiency as well as reduce process emissions.

Out of six industry-wide performance targets, two are directly related to automotive applications. First, the aluminum industry has a goal of increasing aluminum use in automobiles by 40% over 1997 levels by 2002. The second goal is to reduce the cost ratio of aluminum-to-steel to less than 3-to-1 for auto applications (Aluminum Industry Technology Roadmap, 1997, p.33).

Yoshiki-Gravelsins et. al. (1993) briefly mention the Alcoa Smelting Process, an alternative method of aluminum production which uses a bipolar cell and promises to consume only 70% of electricity consumed by Hall-Heroult cells (p.24). Inert anode technology could increase energy-efficiency of electrolysis by up to 25%.

Greenhouse gas emissions

The aluminum industry is a significant emitter of perfluorocarbons (PFCs), a potent greenhouse gas. Thus, one major aluminum industry goal has been to reduce PFC emissions from aluminum smelting: "The U.S. EPA's Voluntary Aluminum Industrial Partnership goal is to reduce U.S. PFC emissions from aluminum smelting by 30 to 60 percent from 1990 levels by the year 2000" (http://www.aluminum.org). A

longer-term solution to the PFC emission problem is inert anode technology. The ability of inert anode technology to reduce greenhouse gas emissions "has been noted by the industry to be the most important national or societal benefit of [this] technology" (Margolis and Eisenhauer, 1998, p.7).

In addition to reducing PFC emissions, the use of inert anodes will eliminate process carbon dioxide emissions associated with the production of today's carbon anodes as well as combustion carbon dioxide emissions by increasing electrolysis process efficiency. Application of inert anodes in the U.S. has the potential to reduce carbon dioxide emissions by 5 million metric tons and PFC emissions by more than 2500 million metric tons (Margolis and Eisenhauer, 1998, p.2)

Mix of power used at aluminum production plants

. As mentioned earlier in this appendix, the mix of fuels used to generate the electricity used in the aluminum production process can vary widely from country to country. Because aluminum production is so electricity intensive, this variation in generating fuels can have a significant impact on emissions from the aluminum lifecycle.

The emission factor for the use of electricity to make aluminum (a version of parameter ENEF from eq. H.3) is calculated in the normal manner in the LEM, using the following parameters: uncontrolled emission rates per unit of fuel input for each type of power plant; the energy efficiency of electricity generation; the generation mix; and emission control extent and effectiveness (see discussions in the main report, and in DeLuchi [1993]). In this calculation, the model uses the actual generation mix in the countries that are producing the aluminum (for use in the target or consuming country), but uses the generation efficiency values and emission control parameters for the *target* or consuming country. The generation mix of each aluminum-producing country is weighted by its contribution to the total vehicle demand of the target consuming country. (The source of aluminum for the U. S. and other countries is given in Appendix B.)

Previously, I assumed that aluminum production plants drew from the U. S. national-average power mix, which is mainly coal-fired. However, Alcoa aluminum (1994) points out that a substantial number of aluminum smelters have been built in conjunction with hydro-electric power plants, and that as a result, hydropower is the primary source of electricity for aluminum plants, worldwide. According to Alcoa (1994), the International Primary Aluminum Institute (IPAI) tracks and publishes the sources of energy used in the aluminum industry. The IPAI's web site has documents that show the following sources of electrical power used by aluminum producers worldwide in 1997 (gigawatthours) (http://www.world-aluminium.org/industry/es002.html):

	Africa	N. America	S. America	Asia	Europe	Oceania	World	% of Total
Hydro	6,986	65,313	31,898	4,317	25,767	7,340	141,621	55.90
Coal	9,530	28,555	0	8,741	11,595	19,633	78,054	30.81

Oil	0	0	0	81	1,264	0	1,345	0.53
NG	0	77	1,036	13,956	3,632	446	19,147	7.56
Nuclear	200	869	116	2	12,013	0	13,200	5.21
Total	16,716	94,814	33,050	27,097	54,271	27,419	253,367	100

In North America, the mix is 69% hydropower, 30% coal, and 1% nuclear. The mix in the U. S. might be a bit lower, because Canada has a considerably higher proportion of hydropower in its overall mix than does the U. S.

With these considerations, the generation mix in aluminum-producing countries is assumed to be as follows:

Aluminum	**generation mix by type**					**notes**
producer	*coal*	*oil*	*gas*	*nuke*	*hydro*	
U. S.	38%	0%	2%	2%	58%	based on discussion above
Canada	19%	0%	0%	1%	80%	based on discussion above
Japan	25%	2%	50%	3%	20%	based on discussion above; alsoIEA data for Japan (see App. B)
Korea	48%	1%	44%	2%	5%	based on discussion above; alsoIEA data for Korea (see App. B)
Germany	43%	0%	17%	19%	5%	IEA data for Germany (see App. B; calculated mix in target year)
N. Europe	5%	0%	5%	20%	70%	based on discussion above; also IEA (2002b) data for Norway, U.K., Netherlands
S. Europe	14%	1%	30%	15%	40%	based on discussion above; also IEA data for Italy (App. B)
FSU	25%	2%	39%	17%	17%	IEA data for Russia (see App. B; calculated mix in target year)
Asian Exporters	67%	2%	1%	1%	30%	IEA data for China (see App. B; calculated mix in target year)
Other	77%	1%	14%	0%	7%	IEA (2002b) data for Australia, year 2000
Generic developed	28%	1%	13%	10%	48%	based on discussion above
Generic LDC	33%	1%	5%	1%	60%	based on discussion above

These changes reduces emissions from materials manufacture by a few percentage points.

Data sources

Information on the production process for primary aluminum: Aluminum Association and Weston (1998), AP-42 (EPA, 1995), EVTECA (ANL et al., 1998), Margolis (1997), Yoshiki-Gravelsins et. al. (1993).

Material and energy data sources: Aluminum Association and Weston (1998), EVTECA (ANL et al., 1998), The Aluminum Association (1998), Margolis (1997), Yoshiki-Gravelsins (1993), Sullivan and Hu (1995), Stodolsky et. al. (1995), Griffiths (1996), Weir and Muneer (1998), Wheeler (1982), Cummings-Saxton (1982), Han (1997), Young and Vanderburg (1995).

Air emissions data sources: Aluminum Association and Weston (1998), AP-42 (EPA, 1995), EVTECA (ANL et al., 1998), Margolis (1997), Yoshiki-Gravelsins et. al. (1993).

Water emissions data sources: Aluminum Association and Weston (1998), Margolis (1997), Yoshiki-Gravelsins et. al. (1993) (listed as net liquid effluents).

SECONDARY (RECYCLED) ALUMINUM

Process description

The production of recycled aluminum is much less energy intensive than that of virgin aluminum. This is because the most energy intensive process in the production of virgin aluminum is the electrolytic separation of the aluminum from the alumina. This step is unnecessary when the input material is scrap aluminum. To make scrap aluminum into new aluminum parts, it must be cleaned, melted, refined, alloyed with any necessary alloying elements, and shaped.

Table H-16 shows inputs and outputs and emissions for secondary (recycled) aluminum production.

Other information

Automotive wrought aluminum products consist of 11% recycled and 89% virgin aluminum. Automotive cast aluminum products consist of 85% recycled and 15% virgin aluminum (The Aluminum Association, 1998; The Aluminum Association and Weston, 1998). Currently, the distribution of aluminum use by product form in automotive applications is made up of 73.8% cast aluminum and the remainder wrought products (The Aluminum Association and Weston, 1998). Thus, the weighted average recycled aluminum content of cars is 0.85*0.738+0.11*0.262 = 65.6%. This value is used in the LEM.

About 80% of the total aluminum content of 1991 cars was recovered from scrap (Stodolsky et. al, 1995). However, in their LCA of automotive materials, Young and Vanderburg (1994) assume that 90% of post-use automotive aluminum is recycled. Das (2000) apparently assumes that about 85% of post-use automotive aluminum is recycled. My assumption is shown in Table H-6.

Data sources

Information on the production process for secondary aluminum: Aluminum Association and Weston (1998), AP-42 (EPA, 1995), EVTECA (ANL et al., 1998).

Material and energy data sources: Aluminum Association and Weston (1998), EVTECA (ANL et al., 1998), The Aluminum Association (1998), Das et. al. (1995), Sullivan and Hu (1995), Stodolsky et. al. (1995), Weir and Muneer (1998), Wheeler (1982).

Air emissions data source: Aluminum Association and Weston (1998), EVTECA (ANL et al., 1998).

PLASTICS

Process description

Plastics are made mainly from fossil fuel feedstocks. First, fossil fuels are separated into their component parts via a process called "cracking," then, the components are combined into polymer molecules to make a plastic. Depending on exactly which monomers are strung together in which way, different kinds of plastics result with different properties for different applications. The main plastics that are widely used in vehicles are polyurethane, polyester (PET), polyvinyl chloride (PVC), and polypropylene (PP). The manufacture of most plastics involves an enclosed reaction or polymerization step, a drying step, and a final treating and forming step. The embodied energy values available for plastics generally do *not* include the energy necessary to extract and refine the oil or natural gas from which the monomers are made. Therefore, in the LEM, the oil and natural gas feedstocks are counted separately as energy inputs to the manufacture of plastics.

Tables H-17, H-18, and H-19 show inputs and outputs and emissions for polypropylene, polyester, and other plastics.

Data sources

Information on the production process for plastics: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995)

Material and energy data sources: EVTECA (ANL et al., 1998), Wheeler (1982), Cummings-Saxton (1982), Das et. al. (1995), Han (1997), Gaines and Singh (1995), Sullivan and Hu (1995), Stodolsky et. al. (1995).

Air emissions data sources: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995).

SYNTHETIC RUBBER

Data sources

Copolymers of styrene and butadiene containing less than 45 percent styrene by weight are known as styrene-butadiene rubber (SBR), or synthetic rubber. SBR used in vehicle tires uses these monomers in a 1:4 styrene to butadiene ratio. The copolymers are generally produced through the emulsion crumb process. In this process, styrene and butadiene are combined in a series of reactors. About 60 percent of the styrene and butadiene is polymerized into latex. The latex is separated from the rest and combined with an acid and brine solution, which causes it to become 'crumbs' of SBR. These crumbs of SBR are separated, dried, and baled for shipment.

In the making of vehicle tires, a further process called vulcanization is necessary to sufficiently harden the synthetic rubber for roadway wear. In this process, the SBR is combined with sulfur and carbon black and heated. The average tire is comprised of about 45 parts carbon black to 100 parts rubber.

Table H-20 shows inputs and outputs and emissions for synthetic rubber production.

Data sources

Information on the production process for rubber: AP-42 (EPA, 1995), EVTECA (ANL et al., 1998).

Material and energy data sources: EVTECA (ANL et al., 1998), Sullivan and Hu (1995), Stodolsky et. al. (1995), Han (1997).

Air Emissions data sources: EVTECA (ANL et al., 1998), AP-42 Section 6.10, Synthetic Rubber (EPA, 1995).

GLASS

Process description

The two main types of glass used in automobiles are float glass and textile fiberglass. The production processes for these two types of glass are similar. The first step, batch preparation/formulation, consists of preparing the specific proportions of raw materials to yield the desired glass type. In the second step, melting and refining, raw materials are melted, bubbles are removed from the mixture, and the fluid is homogenized. The melting and refining stage accounts for between 50 and 68 percent of the energy used in glass production.

Float glass is used for automotive applications where flat glass is needed such as windows, windshields, etc. It is made flat by pouring molten glass onto a bath of molten tin. The first time it is cooled, the glass is cooled slowly to relieve internal stresses. Automotive flat glass is strengthened by heating the glass and then rapidly cooling it with forced air at ambient temperatures. Finally, windshield glass is laminated.

Textile fiberglass is used to strengthen composite automotive materials such as sheet molding compound (SMC). It is made by pouring molten glass into a "heated forming bushing with tiny holes in the bottom. As the molten glass passes through the holes, it is cooled to form continuous fibers. The fibers are then chemically coated and made into strands or yarns" (Ruth and Dell'Anno, 1997, p.113).

Table H-21 shows inputs and outputs and emissions for float glass. Table H-22 shows inputs and outputs and emissions for textile fiberglass.

Energy efficiency and the future of the industry

In the last 15 years, higher production rates and advanced refractories used by the flat glass sector have reduced fuel consumption per ton of glass melted by 25 percent. Since 1978, energy use in the fiberglass segment has declined by almost 30 percent (Glass: A Clear Vision for a Bright Future, 1996).

There are opportunities for further improvements. According to Shepard (1999), 1/4 of the formed glass produced in an automotive glass plant must currently be remelted due to poor product quality. Minimizing this waste would save significant amounts of energy and reduce costs and emissions.

Technological improvements could reduce energy use in the melting step of glass making. According to Ruth (1997), "state-of-the-art technologies … could reduce the energy use in this stage [melting] by 8-37% from current average practices. Advanced technologies … could reduce energy consumption by an additional 38-63%" (p. 12). The thermodynamic minimum energy requirement for melting glass is 2.2 million BTU/ton; by comparison, the amounts embedded in the data of Tables H-21 and H-22 for this step are 8.1 million BTU/ton for float glass and 9.89 million BTU/ton for textile fiberglass. (The difference between float glass and fiberglass appears to be due to the difference in material composition for the two types of glass.)

The use of recycled glass (cullet) could in principle reduce the energy requirements of glass use. Unfortunately, the high quality requirements of flat glass and textile fiberglass currently preclude the use of post-consumer cullet (Ruth, 1997, p.114).

Data sources

Information on the production process: Ruth and Dell'Anno (1997), EVTECA (ANL et al., 1998), Balestrini and Levizzari (1997), AP-42 (EPA, 1995).

Material and energy data sources: Ruth and Dell'Anno (1997), EVTECA (ANL et al., 1998).

Air Emissions data sources: EVTECA (ANL et al., 1998), Ruth and Dell'Anno (1997), AP-42 (EPA, 1995), Balestrini and Levizzari (1997).

PRIMARY (VIRGIN) COPPER

Process description

Copper is desirable for use in automotive applications that require a highly conductive metal. These include radiators and copper wiring. Aluminum can replace copper for these uses (and has in many stationary applications), but greater bulk is required for comparable performance. Mobile applications must be space-saving, however, and copper has remained the conducting material of choice.

Copper is produced from ore that is less than 1 percent copper, making pure copper production highly energy intensive. There are three different kinds of ore that contain copper, but copper sulfide ore is represented here as it is the most common in the United States. After the copper sulfide ore has been mined, it is crushed, ground, and then concentrated using flotation purification to between 15 and 35% copper. This concentrate is smelted and converted to 98-99.5% "blister copper". The smelting process consists of roasting to reduce impurities, smelting to produce a molten mixture that is between 35 and 65 percent copper, concentrating to the blister copper stage by oxidizing iron and sulfur impurities and removing the slag, and fire or electrolytic refining.

Table H-23 shows inputs and outputs and emissions for primary (virgin) copper.

Industry future and energy efficiency

Copper producers are concerned about energy use and are working toward using less energy in the production processes. While copper processing has become more energy-efficient, environmental standards have also become more stringent[7] and ore grades have declined. Therefore, copper production remains an energy-intensive industry.

The breakdown of [copper production] by process operation [with respect to energy use] is approximately as follows: 20% open-pit mining, 50% concentration, 17% smelting, and 13% refining (Alvarado et. al., 1999, p.309). Indirect energy use in copper production (the energy used to manufacture the extra Materials that are used in the copper production process) may reach 45% and 75% of the total in pyrometallurgical and hydrometallurgical technologies, respectively (Alvarado et. al., 1999, p.309).

Emissions

To separate the sulfur from the copper in the copper sulfide ore, the sulfur is oxidized, forming large amounts of sulfur dioxide. In fact, a byproduct of copper production is sulfuric acid, or sulfur dioxide mixed with water. However, some of the SO_2 does not get transformed into this usable product and must be treated as an air emission.

Copper has particularly high effluent emissions due to the large amounts of water used in the initial concentration process using flotation purification. Typically, 2.5–3.0 cubic meters per second of water are used per ton of refined copper. Especially

[7] Environmental considerations apparently can significantly impact energy use: Alvarado et al. (1999) note that in an actual flash copper smelter plant, only 25% of energy consumption goes to production, with the balance going to environmental control.

in arid areas, water recirculation (up to 85% in new projects) is a common practice (Alvarado et. al., 1999, p.310)

Data sources

I*nformation on the production process for primary copper:* EVTECA (ANL et al., 1998), AP-42 (EPA, 1995), Alvarado et. al.(1999).

Material and energy data sources: EVTECA (ANL et al., 1998), Alvarado et. al.(1999), Yoshiki-Gravelsins et. al. (1993), Han (1997), Sullivan and Hu (1995), Stodolsky et. al. (1995), Gaines and Singh (1995).

Air Emissions data sources: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995).

Water Emissions data sources: EVTECA (ANL et al., 1998).

SECONDARY (RECYCLED) COPPER

Recycled copper is much less energy-intensive to produce than primary copper. Production steps include scrap pretreatment, smelting, alloying and casting. EVTECA (ANL et al., 1998) reports that secondary copper production requires between 3,000 and 21,000 BTU/lb, depending on the purity of the scrap metal. Exactly which steps are included in these figures is unclear. In addition to the energy requirement advantages of secondary copper over primary copper, there is a large reduction in the emissions of SO_2. Although the EVTECA (ANL et al., 1998) report includes this information on secondary copper production (in a footnote), the EVTECA (ANL et al., 1998) group did not consider secondary copper to be an input to vehicle production. However, according to the EPA's AP-42 (EPA, 1995), approximately 40 percent of the copper used in the United States was recycled copper in 1992. Whether this recycled copper was put into automobiles is unclear.

In the absence of information on emissions from the production of recycled copper, we assume that SO_2 and TSP emissions are 10% of those from the production of virgin copper.

PRIMARY (VIRGIN) LEAD

Process description

Lead is produced through a series of metallurgical processes, starting with lead sulfide ore concentration at the mine, continuing with sintering to reduce the sulfur content of the ore, and finishing with reduction in a blast furnace and refining in kettles. The tables below represent only the reduction stage of this series of processes. Fuel other than metallurgical coke is used in the other processes. Information about the amounts of other types of fuel used was unavailable.

Table H-24 shows inputs and outputs and emissions for primary (virgin) lead production.

Data sources

Information on the production process for primary lead: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995)

Material and energy data sources: EVTECA (ANL et al., 1998)

Air Emissions data sources: EVTECA (ANL et al., 1998)

SECONDARY (RECYCLED) LEAD

Process description

More than 60 percent of scrap for secondary lead production comes from recycled batteries. Secondary lead production involves scrap pretreatment, smelting, and refining. Scrap pretreatment is completed through battery crushing followed by heating to 'sweat' the lead (which has a relatively low melting point) out of the crushed battery. Smelting is done in blast, reverbatory, or rotary kiln furnaces and further separates the lead from scrap contaminants and also reduces the lead oxides to pure lead. Refining of secondary lead is very similar to virgin lead refining.

Lead is one of the most highly recycled materials in the world. The percentage of secondary lead in any lead product – including automobile lead applications – is high.

Table H-25 shows inputs and outputs and emissions for secondary (recycled) lead production. The table is incomplete because some information was not available.

Data sources

Information on the production process for secondary lead: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995)

Material and energy data sources: EVTECA (ANL et al., 1998), Sullivan and Hu (1995), Han (1997), Das et. al. (1995), Gaines and Singh (1995)

Air Emissions data sources: EVTECA (ANL et al., 1998), AP-42 (EPA, 1995)

OTHER MATERIALS

Concrete and cement

Cement is an integral part of concrete, which is one of the most important building materials in the world. Worrel et al. (2001) estimate that cement manufacture contributes 5% to global anthropogenic emissions of CO_2.

I consider five sources of CO_2 in the production of cement and concrete: (1) the use of energy to make cement, (2) the conversion of $CaCO_3$ to CaO in the manufacture of cement, (3) the use of energy to transport cement and make bags for cement, (4) the use of energy to process and transport gravel, and (5) the use of energy to make

concrete from the primary ingredients. The treatment of these in the Lifecycle Emissions Model (LEM) is discussed below.

Background. Cement is made up of a material called "clinker", and other filler, such as gypsum or ash. For example, Portland cement is 95% clinker and 5% gypsum (Worrel et al., 2001).

Clinker, in turn, is about 2/3 lime (calcium oxide, CaO) and 35% silicon, iron, and aluminum oxides (Worrel et al., 2001). Lime is produced from limestone via the following reaction, which produces CO_2:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad \text{eq. H.29}$$
$$1\text{ kg} \rightarrow 0.56\text{ kg} + 0.44\text{ kg}$$

Finally, concrete is about 15% cement, and 85% gravel and filler (see DeLuchi, 1993).

1). Use of energy to make cement. Estimates reviewed in DeLuchi (1993) indicate about 2500 BTU/lb. of cement, counting electricity at 3412 BTU/kWh. However, in their comprehensive recent review of CO_2 emissions from the cement industry, Worrel et al. (2001) provide much lower estimates:

	Industrialized countries	Rest-of-world
Fuel input (gJ/10^6 g -cement; BTU/lb)	2.9; 1250	3.7; 1500
Electricity (gJ-elec./10^6 g-cement; BTU-elect./lb)	0.3; 130	0.4; 170

Worrel et al. (2001) write that emissions of CO_2 can be reduced by improving the energy efficiency of traditional processes, shifting to more efficient processes, shifting to low-carbon process fuels, and using blended fuels with a lower clinker/cement ratio. The also discuss the longer-range possibilities of using mineral-polymer cements and scrubbing CO_2 from flue gasses. Some of the improvements they discuss can reduce energy intensity by on the order of 30%.

I assume a total of 1500 BTU/lb for industrialized countries and 1800 BTU/lb for rest-of-world (including electricity at 3412 BTU/kWh), and then assume that fuel intensity decreases by 0.4%/year from the year 2000 value. I assume that 55% of the energy input is coal, 30% is natural gas, 5% is oil, and 10% is electricity.

2). The conversion of $CaCO_3$ to CaO in the manufacture of cement. The production of CO_2 from the calcination process is calculated simply as the product of:

weight ratio of CO_2 to CaO produced (0.44/0.56 = 0.79, from eq. H.29)
weight ratio of CaO to clinker (0.66, Worrel et al., 2001)
weight ratio of clinker to cement (0.85, Worrel et al., 2001).

The result is 0.44 kg-CO_2/kg-cement. I use this value in the LEM.

3-4). The use of energy for cement transport, and to process and transport gravel. DeLuchi (1993) reports an estimate of about 100 BTU/lb to make bags for and transport cement. In the LEM, transportation of materials is represented explicitly as a function of tons shipped by mode, the distance shipped by mode, and the energy intensity of each mode (see the main report). The LEM has two such material-transport categories: short distance and long distance. I assume that most transport of cement and concrete is short distance; in the LEM, the parameter assumptions for this category result in about 100 BTU/lb, due mainly to truck transport.

5). The use of energy to make concrete from the primary ingredients. I assume that this is 10% of the energy required to make a lb. of cement. The final calculation assumes that concrete is 15% cement by weight (DeLuchi, 1993).

ENERGY USE IN AND EMISSIONS FROM THE TRANSPORTATION OF FINISHED MATERIALS AND MOTOR VEHICLES

Background

As explained above, our estimates of energy use in the production of materials (parameter EEN in eq. H.2) do not include energy use in and emissions from transportation of finished materials, semi-fabricated products, parts, and vehicles to end users. These transportation emissions are estimated separately here.

The LEM explicitly characterizes the transportation of the following vehicles, materials, and chemicals:

- light-duty vehicles (LDVs)
- heavy-duty vehicles (HDVs)
- automotive stampings (included in the LEM in the category "assembling and transporting vehicles")
- automobile engines (included in the LEM in the category "assembling and transporting vehicles")
- automobile parts (included in the LEM in the category "assembling and transporting vehicles")
- steel (used for plain carbon steel, high-strength steel, stainless steel, recycled steel, and iron)
- aluminum (used for virgin and recycled aluminum)
- plastics (used for advanced composites and other plastics)
- other materials short distance (recycled copper, recycled lead, cement, concrete, limestone
- other materials long distance (all other materials)
- agricultural chemicals (see the discussion in the main documentation report)
- fertilizer minerals (included in an explicit calculation of the lifecycle of agricultural chemicals, in this appenidx)

The general method for estimating transportation emissions is:

$$ETR_{M,P,T} = \sum_{D} TS/TP_{M,D} \cdot LH1W_{M,D} \cdot EI_{M,D,T_B} \cdot \left(1 + \frac{\Delta EI_{M,D}}{100}\right)^{T-T_B} \cdot TREM_{P,D,T}$$

eq. H.30

where:

$ETR_{M,P,T}$ = emissions of pollutant P from the transportation of finished material M in target year T (g-P/ton-M; converted to g/lb. in the LEM)

$TS/TP_{M,D}$ = tons of material M shipped by mode D per ton of M produced (discussed below)

$LH1W_{M,D}$ = the one-way length of haul per average ton of M by mode D (miles) (discussed below)
$EI_{M,D,Tb}$ = the energy intensity of mode D hauling material M in base year T_B (BTU/ton-mile) (see main documentation report)
$\Delta EI_{M,D}$ = the annual percentage change in the energy intensity of mode D hauling material M (see main documentation report)
$TREM_{P,D,T}$ = lifecycle emissions of pollutant P from the use of energy by transportation mode D in year T (g-P/BTU) (see main documentation report)
subscript M = material being transported
subscript D = transportation distribution mode (domestic ship, ocean-going freighter [for imports], rail, pipeline, or truck)
subscript P = pollutants
T_B = base year for energy intensity data
T = target year of the analysis

The data on emission factors (TREM) and BTU/ton-mile energy intensity (EI and ΔEI) are discussed in the main report. In the following sections, I discuss the data used to estimate miles of shipment, and tons shipped/ton-produced. I discuss domestic transportation separately from international shipping because the data sources for the two are different.

Domestic transport

In general, miles of shipment can be estimated directly from data in the Bureau of the Census's *Commodity Flow Survey (CFS).* Tons-shipped/ton-produced must be calculated as a ratio. Tons shipped (the numerator) can be estimated from data in the *CFS;* tons produced (the denominator) must be estimated from other sources.

There is a 1993 *CFS* (Bureau of the Census, 1996) and a 1997 *CFS* (Bureau of the Census, 1999). Both publish data on tons shipped and average length of haul, by mode, for various commodities. In the 1993 *CFS*, commodities are classified by STCC (Standard Transportation Commodity Classification). In our analysis of the lifecycle of materials, the following STCCs from the 1993 *CFS* (Bureau of the Census, 1996) are relevant:

101 Iron ores
105 bauxite ores or other aluminum ores
109 miscellaneous metal ores
282 plastic materials or synthetic fibers, resins, or rubber
301 rubber tires or innertubes
331 steel works, rolling mill, or other reduction plant products
332 iron or steel castings
333 nonferrous metal primary smelted products

335 nonferrous metal basic shapes
336 nonferrous metal or nonferrous metal base alloy castings
346 metal stampings (includes automotive, 3465)
351 engines or turbines (includes some diesel engines, 3519)
369 miscellaneous electrical machinery, equipment, or supplies (includes engine accessories, 3694, and car batteries, 3691)
371 motor vehicles or equipment (includes automotive parts, 3714)

The Bureau of the Census (1996) reports the following average shipment distances (miles) from the 1993 *CFS*:

STCC	all modes	private truck	for-hire truck	rail	truck and rail	other
101	325			314		
105	528		500			
109	465			563		
282	740	86	517	989		
301	207	62	496	1446		
331	199	61	315	732		
332	262	56	437	581		
333	346	65	492	1067		
335	308	79	624	1679		
336	611	63	877			
346	580	73	517	679		
351	379	156	580			
369	472	38	714	1502		
371	275	33	419	957	1460	149

The Bureau of the Census (1996) also reports the following thousand tons shipped from the 1993 *CFS*:

STCC	all modes	private truck	for-hire truck	rail	truck and rail	other
101						
105						
109						
282						
301						
331						
332						
333						
335						
336						
346	14356	3545	8243	1814		
351						
369	3791	1607	2006	23		
371	75646	13650	37586	8264	7583	7299

The 1997 *CFS* (Bureau of the Census, 1999) uses a different and in some cases more useful classification system, based on the "Standard Classification of Transported Goods" (SCTG):

141 Iron ores and concentrates
241 plastics in primary forms, rubber in primary forms or sheets, and unvulcanized rubber compounds
243 rubber articles
321 iron and steel in primary forms, semifinished forms, or in powders or granules, and ferroalloys
322 flat-rolled products of iron or steel
324 nonferrous metal, except precious, in unwrought forms, in finished basic shapes, or in powders or granules
341 internal combustion piston engines
361 motor vehicles for the transport of less than 10 people, except parts
362 motor vehicles for the transport of goods and road tractors for trailers, except parts
364 parts and accessories for motor vehicles

From the1997 *CFS* (Bureau of the Census, 1999) I extract data on ton-miles and tons shipped, and calculate average miles per ton, for SCTGs 341, 361, 362, and 364 (Table H-26).

To represent transport of materials and automotive stampings, I use data from the *1993 CFS*, shown above. In the case of automotive stampings, I start with the data for STCC 346, "metal stampings". I assume that 60% of the metal stampings here are automotive stampings specifically. Then, I estimate miles per average ton, by mode, by dividing Census-reported ton-miles by Census-reported tons (not shown here) for each mode. (I do this, rather than use the average distances reported by the Census, in order to be able to disaggregate the "truck and rail" category. The resulting estimated distances are close to the average distances reported by the Census (1996; shown above). To estimate tons-shipped/ton-produced, by mode, I divide 60% of the tonnage reported for STCC 346 by the total amount of motor-vehicle shipped in 1993. The reported tonnage is shown above. I estimate that in 1993, 22 million tons of vehicles were produced for use in the U. S. (based on Delucchi [1996] with accounting for foreign production for the U. S. market). For example, I estimate (3545+8243)*0.60/22000 = 0.32 tons of automotive stampings shipped by truck for every ton of motor-vehicle produced.

For the generic "steel,", "aluminum," "plastic," and "other materials" categories in the LEM, I estimate average distances on the basis of the data for STCCs 101, 105, 109, 282, 331, 332, 333, 335, and 336, from the 1993 *CFS*. I estimate tons/ton assuming that most shipment occurs by rail.

To represent the shipment of LDVs, HDVs, parts, and engines, I use the *1997 CFS* data (Bureau of the Census, 1999) for SCTGs 341, 361, 362, and 364, shown in Table H-26. I use the miles/ton estimates as shown in Table H-26. To estimate tons-shipped/ton-produced, I divide tons shipped by mode (Table H-26) by the total amount of vehicle tonnage produced for sale in the U. S. in 1997 (Table H-27).

International transport of imported materials

The U. S. Census sources discussed above cover only domestic shipments. Hence, other data are used to estimate length of haul (LH1W) and tons-shipped/ton-produced (TS/TP) for imported materials. In the case of LH1W, a weighted-average shipping distance for imported materials is estimated on the basis of the quantity of imports of each material from each source (exporter) and the shipping distance from each exporter to the U. S.:

$$LH1WI_{M,C} = \frac{\sum_{PM} CM_{M,PM,C} \cdot LH1W_{PM,C} \cdot FIW_{M,PM,C}}{TS/TPI_{M,C}} \qquad \text{eq. H.31}$$

where:

$LH1WI_{M,C}$ = the ton-weighted average length of haul, by international ocean transport of material M used by country C (miles)

$CM_{M,PM,C}$ = the contribution of material-producing country PM to the total supply of material M in country C (as a fraction of total supply of M in C) (discussed below)

$LH1W_{PM,C}$ = the length of haul between material-producing country PM and material-consuming country C (miles; data from the Defence Mapping Agency [1985], or estimated from an international atlas)

$FIW_{M,PM,C}$ = of the total material M produced by country PM for country C, the fraction that is shipped to C via international water (assumed to be 0.0 for PM = C [domestic production] and for any two countries that have extensive pipeline, rail, or road transport between them; 1.0 for all other PM-to-C supply)

$TS/TPI_{M,C}$ = of total supply of material M in country C, the fraction that is imported (Appendix B)

subscript M = imported (traded) materials (LDVs, HDVs, steel, aluminum, plastics, other)

subscript PM = material exporting countries (U. S., Canada, Japan, Korea, Germany, Northern Europe, Southern Europe, Former Soviet Unions, Asian Exporters, other)

Finally, I do not explicitly represent trade in engines, parts, and stampings, but rather assume that 5% of stampings and 10% of engines and parts are imported, an average distance of 7,000 miles.

ENERGY USE AND EMISSIONS IN MOTOR-VEHICLE ASSEMBLY

General method

Total emissions from motor vehicle assembly are the sum of energy-related emissions and process-area emissions. Energy related emissions are calculated as the product of fuel- usage rates and fuel-usage emission factors. Formally:

$$ERVA_{P,V} = EPR_{P,V} + \sum_{F} ENR_{F,V} \cdot ENEF_{F,P} \qquad \text{eq. H.32}$$

where:

$ERVA_P$ = emissions of pollutant P from vehicle assembly, per lb. of vehicle (g-P/lb.-vehicle)

$EPR_{P,V}$ = emissons of pollutant P from process areas in vehicle assembly (grams-P/lb.-vehicle) (VOC emissions from the use of paint and solvents; discussed in the next subsection)

$ENR_{F,V}$ = energy-usage rate: BTUs of fuel F input in the assembly of vehicles, per lb. of vehicle (BTUs-F/lb.-vehicle) (discussed briefly below)

$ENEF_{F,P}$ = lifecycle emissions of pollutant P from the use of a unit of fuel F (including electricity) in the assembly of vehicles (grams-P/BTU-F) (discussed in the main text and in DeLuchi [1993]; note that electricity emission factors are based on 3412 BTU/kWh)

In the original documentation to the LEM (DeLuchi, 1993), I estimate total BTUs/lb.-vehicle for assembly using data on total energy requirements at automobile assembly plants and the total weight of vehicles assembled. I then compare this with estimates from the literature, and settle on a figure of 4800 BTU/lb. in the U. S., excluding final transportation vehicles, which is handled separately here (see the previous section of this appendix). This is disaggregated into individual fuels using data from the EIA's *Manufacturing Energy Consumption Survey*; the current figures in the LEM are 41% natural gas (in industrial boilers) 17% coal (in industrial boilers), 7% fuel oil (in industrial boilers), and 35% electricity.

Emissions and energy use in the motor-vehicle major producing regions of the world. As mentioned in the introduction, the LEM represents international trade in motor vehicles. For each consuming country, the LEM represents the fraction of total motor-vehicle demand that is satisfied by each of the major motor vehicle producing countries. In the case of vehicle manufacture, two parameters can vary by producing country: i) the energy requirements of manufacture, in BTU/lb (parameter ENR above), and ii) the mix of fuels used to generate the electricity used by motor-vehicle manufacturers (a version of paraemter ENEM above).

As explained earlier with regards to the estimation of the energy requirements of material production, I estimate the BTU/lb. energy requirement in other countries relative to that in the U. S. I assume that the following:

- Germany, France, Japan: 5% less than in the U. S.
- Canada, Korea, Other Europe, and generic developed countries: same as U. S.
- Mexico: 10% more than U. S.
- Generic developing country: 15% more than in the U. S.
- Other: 5% more than in the U. S.

The emission factor for the use of electricity to assemble automobiles (a version of parameter ENEF from above) is calculated in the normal manner in the LEM, using the following parameters: uncontrolled emission rates per unit of fuel input for each type of power plant; the energy efficiency of electricity generation; the generation mix; and emission control extent and effectiveness (see discussions in the main report, and in DeLuchi [1993]). In this calculation, the model uses the actual generation mix in the countries that are producing the vehicles (for use in the target or consuming country), but uses the generation efficiency values and emission control parameters for the *target* or consuming country. (Ideally, one would use generation efficiency and emission control parameters as well as generation mix parameters specific to the actual

producing countries, but for simplicity I chose to use producing-country-specific values for only the most important of these – generation mix.)

The generation mix of each vehicle-producing country is weighted by its contribution to the total vehicle demand of the target consuming country. The source of vehicles for the U. S. and other countries is given in Appendix B. The generation mix in vehicle-producing countries is assumed to be as follows (year 2020, except as noted):

Vehicle	**generation mix by type**					**notes**
producer	*coal*	*oil*	*gas*	*nuke*	*hydro*	
U. S.	53%	6%	7%	25%	8%	analysis of actual generation mix for motor vehicles (DeLuchi, 1993)
Canada	12%	0%	3%	33%	51%	IEA data for Canada (see App. B; calculated mix in target year)
Germany	51%	1%	10%	30%	5%	IEA data for Germany (see App. B; calculated mix in target year)
France	6%	1%	3%	77%	13%	IEA (2002b) data for year 2000
Other Europe	30%	15%	25%	10%	20%	My assumptions
Mexico	9%	48%	20%	4%	16%	IEA data for Mexico (see App. B; calculated mix in target year)
Japan	19%	15%	26%	30%	9%	IEA data for Japan (see App. B; calculated mix in target year)
Korea	39%	8%	13%	37%	2%	IEA data for Korea (see App. B; calculated mix in target year)
Other	38%	10%	14%	18%	19%	My assumptions
Generic developed	55%	10%	20%	10%	3%	My assumptions
Generic LDC	65%	5%	15%	0%	10%	My assumptions

VOC emissions from assembly plants

Motor-vehicle assembly plants emit substantial amounts of volatile organic compounds (VOCs) from the use of paint and solvents. In 1997, the U. S. Environmental Protection Agency's Common Sense Initiative published the results of a detailed analysis of VOC emissions from automobile assembly plants nationwide (EPA, Common Sense Initiative, 1997). The Initiative obtained emissions data from automobile manufacturing plants and from state offices responsible for emissions inventories. In some cases, the facilities reported the emissions themselves; in others, state agencies

calculated emissions on the basis of production levels and emission factors (EPA, Common Sense Initiative, 1997, p. I-37).

The EPA reported that 3 plants emitted 0 to 5.0 lbs VOCs/vehicle, 9 plants emitted 5. 1 to 10.0 lbs/vehicle, 20 plants emitted 10.1 to 15.0, 3 emitted 15.1 to 20.0, and 4 emitted more than 20.0. Plants in nonattainment areas emitted about 11 lbs/vehicle, where as plants in attainment areas emitted about 15 lbs/vehicle. Assuming an average of 12 lbs/vehicle (based on the midpoints of the ranges given above) and 140,000 lifetime miles/vehicle, the plant VOC emissions correspond to 0.04 g/mi -- a small but nontrivial fraction of vehicle tailpipe emissions.

I assume that uncontrolled plants emit 20 lbs/vehicle and that controlled plants emit 6 lbs/vehicle, and that controls were phased in beginning in 1990. I express emissions in g-VOCs/lb-vehicle, assuming that the average vehicle produced in U. S. assembly plants weighed 3800 lbs (all vehicles types; based on Delucchi [1996]).

ENERGY USED TO MANUFACTURE AGRICULTURAL CHEMICALS

In the previous version of the model, the estimates of the energy requirements for fertilizer were based on a review of the estimates of others. I have replaced these with estimates derived from primary survey data, from the Census and the EIA, on energy input and product output at the mining, transport, and manufacturing stages.

According to Bhat et al. (1994), the fertilizer industry researched, developed, and adopted significant energy saving techniques beginning in the late 1970s and continuing through the mid 1980s (no doubt in reaction to the energy crises of the 1970s, and high oil prices of the early 1980s). Bhat et al. (1994) themselves make detailed estimates of the energy inputs to the lifecycle of fertilizers, based on 1987 data on energy use in fertilizer manufacture, and earlier data regarding energy use at other stages of the lifecycle. However, because the recent primary data from the EIA and the Census are about a decade more current than the data of Bhat et al. (1994)[8], and reflect all of the energy-efficiency measures adopted through the mid 1980s, I have done an original analysis of energy inputs into the fertilizer lifecycle, rather than rely on the more detailed but less current estimates of Bhat et al. (1994).

Although the energy-input/product-output estimates are not particularly complex, neither are they completely straightforward. There are in general four kinds of problems that must be faced. First, primary data are not available for every stage of all of the chemical lifecycles. Second, the survey data that are available have deficiencies. Third, the scope of the energy input data and the scope of the product output data rarely match precisely. Fourth, because fertilizer use is reported in nutrient tons, as opposed to material tons, one must estimate the relationship between material tonnage

[8]None of these data were available when Bhat et al. were doing their research.

and nutrient tonnage. These issues are discussed in more detail as they arise in particular contexts.

The lifecycle of nitrogen, phosphate, and potash fertilizers

The major fertilizers, or "macro nutrients," are nitrogen, expressed in terms of elemental N; phosphate, expressed in terms of P_2O_5; and potash, expressed in terms of K_2O. The lifecycle of potash is the simplest. Virtually all of the potash used in agriculture is potassium chloride (Taylor, 1994), KCl, which is a refined product of potassium mining establishments (Bureau of the Census, *1992 Census of Manufacturers, Agricultural Chemicals* , 1995). Hence, the energy lifecycle of potash comprises energy inputs to:

Potash:
- mine production of KCl
- transportation of KCl
- mixing of fertilizer for sale

The lifecycles of phosphate fertilizers are more complex. There are several different kinds of phosphate fertilizer (Taylor, 1994; Bureau of the Census, *Current Industrial Reports,* 1997), and several major inputs into the manufacturing process (Bureau of the Census, *1992 Census of Manufacturers, Agricultural Chemicals* , 1995). I will treat the two major inputs, phosphate rock and sulfur, in detail, and then scale these calculated results to account for other inputs. Thus, the energy lifecycle of phosphate fertilizer comprises energy inputs to:

Phosphate fertilizer:
- mine production of phosphate rock
- production of sulfur
- transportation of phosphate rock and sulfur
- manufacture of fertilizer
- production of materials other than phosphate rock and sulfur
- mixing of fertilizer
- transport of finished fertilizer

The lifecycles of nitrogenous fertilizers are the most complex of all -- too complex, in fact, to be characterized in detail. Consequently, I will estimate energy use at the major manufacturing stage, and then apply a scaling factor to account for energy inputs to the materials input to the manufacturing stage:

Nitrogen fertilizer:
- manufacture of fertilizer in SIC 2873
- production of materials input to SIC 2873
- mixing of fertilizer

• transport of finished fertilizer

Potash

Mineral mining. The *1992 Census of Mineral Industries, Fuels and Electric Energy Consumed* (Bureau of the Census, 1997) reports energy consumed by industries that mine fertilizer and chemical minerals: SIC 1474, potash, soda, and borate mining; SIC 1475, phosphate rock mining; and SIC 1479, fertilizer and chemical mineral mining not elsewhere classified. The Bureau of the Census, *1992 Census of Mineral Industries, Chemical and Fertilizer Mineral Mining,* (Bureau of the Census, 1995) reports the tons of minerals shipped from the same industries, in 1992. With these two data sources, one can estimate the amount and kind of energy use per lb of fertilizer mineral shipped.

There are three considerations in the estimation of this BTU/lb measure. First, the Census data on energy use are not complete: some data are withheld to avoid disclosing information for individual companies, and some energy use (called "undistributed fuels") is reported as dollar expenditure rather than physical energy quantity. I have filled in the withheld data so that all of the individual cells add to the higher level totals shown, and have assumed that the undistributed energy comprises the same mix of fuels as the distributed energy.

Second, and most seriously, much of the data on tons of mineral shipped in 1992 were withheld in order to avoid disclosing data for individual companies. I have estimated the withheld data on the basis of value of shipments, shipments in prior Census years, other data on mineral production, and my judgment.

Third, the energy required to mine a ton of potash specifically might be more or less than the energy required to mine a ton of potash, soda, and borate mineral on average. However, I have no basis for assuming that it is different.

The results of the analysis of mining energy, for industry 1474, are:

	1992	1987	1982
10^3 tons mineral shipped	22,315	19,749	16,901
BTU/lb-mineral	1,530	2,003	2,680

It appears that mining energy has been declining dramatically[9]. I will assume that this trend continues.

The estimates of BTU/lb-fertilizer-mineral must be converted to the BTU/lb-fertilizer-nutrient provided (as N, P_2O_5, and K_2O). This is done by multiplying BTU/lb-fertilizer-mineral by the ratio of the weight of fertilizer minerals to the weight of N, P_2O_5, and K_2O nutrient provided. This ratio is discussed below.

[9]Although it is possible that I have, say, overestimated shipments (recall that the data on shipments in SIC 1474 are incomplete) and hence underestimated BTU/lb in 1987 and 1992, the relatively accurate estimates of BTU/lb in SIC 1475, phosphate rock mining, show the same dramatic decline.

A portion of the energy used in industry 1481, which provides services in support of all industries in major SIC group 14 (mining and quarrying of all non-metallic, non-fuel minerals) should be assigned to the mining of fertilizer and chemical minerals. In 1992, SIC 1481 consumed 1% of the energy consumed by all non-metallic, non-fuel mineral-mining industries in SIC 14. On the assumption that the energy used in SIC 1481 should be allocated to the mining industries of SIC 14 in proportion to energy consumption, I scale the energy use in SICs 1474, 1475, and 1479 by 1.01.

Transport of fertilizer mineral. The Bureau of the Census' *1993 Commodity Flow Survey* (*CFS)* (Bureau of the Census, 1996) reports tons and ton-miles of shipments of chemical and fertilizer minerals (STCC 147: potash, soda, borate, phosphate rock, sulfur, and other chemical and fertilizer minerals) shipped by rail, ship, truck, and other modes, in 1993:

Mode	*10^3 tons*	*10^6 ton-mi*	*calc. miles*
rail	64,968	18,629	287
ship	7,039	5,077	721
truck	25,621	4,654	182
other or unknown	14,243	8,301	583
Total	*111,871*	*36,661*	

I use these data to estimate average ton-shipped/ton-produced. With this ton/ton estimate, the average shipping length shown, and assumptions regarding energy intensity per mode, I can estimate the average BTUs required to transport a lb of any fertilizer mineral. Note that the transport energy thus calculated is expressed per lb of mineral, not per pound of finished fertilizer nutrient. Because fertilizer nutrient is a fraction of the total material, BTU/lb-fertilizer-nutrient will exceed BTU/lb-material. This is addressed below.

Fertilizer mixing. In the Standard Industrial Classification, which serves as the basis of the EIA's and the Census' estimates of manufacturing energy consumption by industry, there is a separate industry engaged in "fertilizer mixing only" (SIC 2875). This industry includes establishments "primarily engaged in mixing fertilizers from purchased fertilizer materials" (Office of Management and Budget, 1987, p. 147). I treat this industry as if it were part of the manufacturing or mining stage: I estimate the total energy in the industry, and allocate the total to each of the three major fertilizers (nitrogen, phosphate, and potash).

Unfortunately, the EIA's *Manufacturing Energy Consumption* survey does not cover SIC 2875. However, the *1992 Census of Manufactures, Agricultural Chemicals* (Bureau of the Census, 1995) does report total electricity consumption (289 million kWh), and total expenditures on fuels in SIC 2875. Comparing these expenditures with the reported expenditures on fuels in SICs 2873 and 2874, and then refering to the EIA's estimates of fuel consumption in SICs 2873 and 2874, I estimate that SIC 2875 consumed

about 10 trillion BTUs of fuel in 1992, mainly as natural gas. This is a relatively small amount.

This total electric and fuel energy can be allocated to the different fertilizer products in proportion to the weight of material handled in the industry. In 1992, SIC 2875 handled 1.95 million tons of nitrogen fertilizers, 0.69 million tons of phosphate fertilizers, and 0.85 million tons of potash fertilizers (Bureau of the Census,*1992 Census of Manufactures, Agricultural Chemicals*, 1995). Hence, I allocate 56% of the energy to nitrogen, 20% to phosphates, and 24% to potash. This allocated energy is divided by total manufacturing output, in the case of nitrogen and phosphates, and total mine output, in the case of potash[10]. The results of this analysis are summarized below:

	10^3 tons	weight share	Electricity (10^6 kWh)	NG (10^{12} BTU)
Nitrogen fertilizer	1952.8	0.56	162	5.59
Phosphate fertilizers	687.8	0.20	57	1.97
Potash fertilizers	852.8	0.24	71	2.44
Total	*3493.4*	*1.00*	*289*	*10.00*

Ratio of material weight to nutrient weight. Fertilizer application is reported not in tons of actual material applied, but in tons of nitrogen (N), phosphate (as P_2O_5), and potash (as K_2O) nutrient. However, the energy required to mine fertilizer minerals, and transport fertilizer minerals and products, is related to and expressed in terms of the total material weight. To express the transport and mining energy per unit of N, P_2O_5, and K_2O provided, we must multiply the energy/total-material-ton by the ratio of material tons to nutrient tons.

The case of potash is simple, because virtually all potash fertilizer is potassium chloride, KCl, a basic mineral produced from potassium mining with essentially no chemical refining. Two moles of KCl (formula mass 74.55 g/mole) are needed per mole of K_2O (formula mass of 94.2); hence, 1.58 tons of KCl ($74.55 \cdot 2 \div 94.2$) provides 1.0 ton of K_2O.

[10]Technically, two other issues should be addressed: imports and exports, and coverage and specialization. It may be that much of the output of SIC 2875 is exported, or, alternatively, that imported fertilizer requires more or less "mixing" than does domestically produced. I do not analyze this. As regards coverage (do industries other than SIC 2875 mix fertilizer?) and specialization (does SIC 2875 do anything other than mix fertilizer?), the Census' data show that SIC 2875 handles 97% of all fertilizer mixing, and that fertilizer mixing is 98% of what SIC 2875 does.

Phosphate

Mining of phosphate rock. With the Census' data on energy use (*1992 Census of Mineral Industries, Fuels and Electric Energy Consumed,* Bureau of the Census, 1997), and net shipments (Bureau of the Census, *1992 Census of Mineral Industries, Chemical and Fertilizer Mineral Mining,* 1995) in SIC 1474, I estimate the amount and kind of energy use per lb of phosphate rock shipped. See the discussion above regarding mining of potash, soda, and borate minerals, in the "Potash" section, for further details. Note that for two reasons, the BTU/lb estimate for phosphate rock is more accurate than the BTU/lb estimate for potash. First, SIC 1475 comprises only phosphate rock mining, whereas SIC 1474 includes borate and soda mining as well as potash mining. Second, the Census estimates of shipments of phosphate rock are complete. Thus, the second and third caveats above regarding the data on potash mining do not apply here.

The results of the analysis of mining energy, for industry 1474, are:

	1992	1987	1982
10^3 tons mineral shipped	58,059	50,744	45,120
BTU/lb-mineral	131	160	238

I assume that the trend of declining energy use continues, albeit less dramatically.

Transport of fertilizer mineral. The Bureau of the Census' *1993 CFS* (Bureau of the Census, 1996) reports tons and ton-miles of chemical and fertilizer minerals (STCC 147: potash, soda, borate, phosphate rock, sulfur, and other chemical and fertilizer minerals) shipped by rail, ship, truck, and other modes, in 1993. See the discussion in the "Potash" section for further details.

Fertilizer manufacture. In 1994, SIC 2874 consumed about 46 trillion BTU of primary energy for all purposes, almost entirely in the form of natural gas (EIA, *Manufacturing Consumption of Energy [MCES] 1994*, 1997; electric energy counted at 3412 BTU/kWh)[11]. In 1992, the value of the primary products (code 2873 ---) of this industry was 91% of the total value of all products (primary + secondary) (Bureau of the Census, *1992 Census of Manufacturers, Agricultural Chemicals* , 1995). Hence, I assign to the production of phosphate fertilizer 91% of the reported total energy consumption in SIC 2873 in 1994.

In 1994, 14.2 million tons of P_2O_5 in phosphate fertilizer (product codes 2874 ---) were shipped in all industries (Bureau of the Census, *Current Industrial Reports* , 1997). In 1992, 92% of all phosphate fertilizers were produced in SIC 2874 (Bureau of the

[11]Note that the EIA's estimates are of *net* primary energy consumed; that is, they *deduct* from consumption any electricity, steam, or other energy sold or transferred out of the plant. Thus, the EIA data properly credit the export of steam from fertilizer plants, which according to Bhat et al. (1994) can be substantial.

Census, *1992 Census of Manufacturers, Agricultural Chemicals* 1995). Hence, I assume that SIC 2874 produced $14.2 \cdot 0.92 \cdot 2000 = 26.1$ billion lbs of P_2O_5 in 1994.

The resulting energy-in/product-out ratio is about 1,600 BTU/lb. For two reasons, this is a lower bound on total energy requirements for the manufacture of nitrogen fertilizer. First, it does not include the energy required to produce the materials other than sulfur and phosphate rock that are input to SIC 2873. Second, the Census' estimate of the weight of shipments, which is the denominator of the BTU/lb estimate, probably overstates the net output of the industry. The Census estimate of total shipments excludes material produced and consumed in the same plant, but includes inter-plant transfers. To the extent that material transferred from plant A to plant B is counted once as an inter-plant transfer, and again as part of the finished output of plant B, the true net output of finished products from SIC 2874 will be overestimated. With these considerations, it does not seem unreasonable to that the true BTU/lb manufacturing energy requirement is 10% higher than the figure just calculated. I assume that the average energy requirement, in BTU/lb, declines slightly.

Sulfur. The phosphate lifecycle includes lifecycle emissions from the sulfur input to the production of phosphate fertilizer. Emissions from the production of sulfur depend on the process; presumably, it takes less energy to recover sulfur from waste streams than to produce sulfur from virgin ore. I assume that 70% of sulfur is recovered from waste streams, at a cost of very little GHG emissions. Emissions from the recovery of the 30% from virgin ore are estimated on the basis of the Census energy use data (*1992 Census of Mineral Industries, Fuels and Electric Energy Consumed,* Bureau of the Census, 1997).

Emissions from sulfur transport are estimated on the basis of data reported in the Census' *1993 CFS* (Bureau of the Census, 1996). See the discussion in the "Potash" section for further details.

Fertilizer mixing. See the discussion in the "Potash" section.

Transport of fertilizer product. The Bureau of the Census' *1993 CFS* (Bureau of the Census, 1996) reports tons and ton-miles of shipments of agricultural chemical (STCC 287: nitrogen fertilizers, phosphate fertilizers, pesticides, and other agricultural chemical; note that the transport of potash fertilizer is covered under "fertilizer minerals," STC 147).

Mode	*10^3 tons*	*10^6 ton-mi*	*calc. miles*
rail	15,747	10,111	642
ship	4,989	4,399	882
truck	47,653	5,705	120
other or unknown	15,503	13,485	870
Total	*83,892*	*33,700*	

(The 1997 CFS [Bureau of the Census, 1999] combines fertilizers and fertilizer minerals into a single category.)

I use these data to estimate average ton-shipped/ton-produced. With this ton/ton estimate, the average shipping length shown, and assumptions regarding energy intensity per mode, I can estimate the average BTUs required to transport a lb of any fertilizer mineral. Note again that the transport energy is expressed per lb of total product material (e.g., NH_3), not per pound of finished fertilizer nutrient (e.g., N). Because fertilizer nutrient is a fraction of the total material, BTU/lb-fertilizer-nutrient will exceed BTU/lb-material. This is addressed next.

Ratio of material weight to nutrient weight. In the case of phosphates, three ratios are of interest:

1) the ratio of the weight of phosphate rock mined and shipped to the weight of P_2O_5 provided;
2) the ratio of the weight of sulfur input to manufacturing to the weight of P_2O_5 provided; and
3) the ratio of the weight of finished fertilizer product shipped to the weight of P_2O_5 provided.

1). *Phosphate rock*. Three different estimates indicate the ratio of phosphate-rock weight to P_2O_5 weight is on the order of 3:1. First, the TRW study cited in Appendix K of DeLuchi (1993) indicates a ratio of 3:1. Second, the Encyclopedia Britannica states that typical phosphate rock beds contain about 30% P_2O_5 . Third, the rock-input/P_2O_5-output ratio for industry 2874, phosphate fertilizers, is almost 3:1. In 1992, this industry consumed 34 million tons of phosphate rock (Bureau of the Census, *1992 Census of Manufactures, Agricultural Chemicals*, 1995). In 1992, all industries shipped about 14 million tons of phosphoric acid and superphosphate fertilizer, as P_2O_5 weight (Bureau of the Census, *Current Industrial Reports*, 1997)[12]. According to the *1992 Census of Manufactures, Agricultural Chemicals* (Bureau of the Census, 1995), SIC 2874 accounted for 92% of the total value of shipments of phosphoric acid and phosphate fertilizer. Hence, the rock-input/P_2O_5-output ratio for industry 2874 was $34/(14 \cdot 0.92) = 2.6$.

2). *Sulfur.* In 1992, the weight of sulfur input to SIC 2874 was 25% of the weight of phosphate rock. If the phosphate-rock/P_2O_5 weight ratio is 3.0, then the sulfur/P_2O_5 weight ratio is 0 .75:1.

3). *Finished fertilizer.* The ratio of the gross weight of superphosphates and other phosphate fertilizer shipped to the weight of the P_2O_5 content shipped, in 1994, was 1.88 (Bureau of the Census, *Current Industrial Reports*, 1997). (The ratio of the weight of pure phosphoric acid to P_2O_5 content is 1.4.) I will assume a value of 1.90 for this industry.

[12]See also the discussion above regarding interplant transfers, in regards to the manufacture of nitrogen fertilizers.

Nitrogen

Fertilizer manufacture. A lower bound on the energy required to manufacture nitrogen in fertilizer can be estimated on the basis of aggregate energy-in/product-shipped data for SIC 2873, nitrogenous fertilizers. The primary products of this industry are anhydrous ammonia, nitric acid, ammonium nitrate, ammonium sulfate, nitrogen solutions, urea, and nitrogen organic fertilizers [Office of Management and Budget, 1987].) These primary fertilizer products have a seven-number code, the first four digits of which are the SIC code of the nitrogen fertilizer industry (2873).

The EIA reports total energy consumed in SIC 2873, and the Census reports total production of fertilizer products (code 2873 --). However, these two figures by themselves do not give the energy-in/product-shipped ratio of interest, because SIC 2873 produces a minor amount of non-fertilizer ("secondary") products, which have a product code that does not begin with 2873, and some industries other than 2873 produce nitrogen fertilizer products, with code 2873 ---.

In 1994, SIC 2873 consumed over 600 trillion BTU of primary energy for all purposes, almost entirely in the form of natural gas (EIA, *MCES 1994*, 1997; electric energy counted at 3412 BTU/kWh). In 1992, the value of the primary products (code 2873 ---) of this industry was 94% of the total value of all products (primary + secondary) (Bureau of the Census, *1992 Census of Manufacturers, Agricultural Chemicals* , 1995). Hence, I assign to the production of nitrogen fertilizer 94% of the reported total energy consumption in SIC 2873 in 1994.

The Bureau of the Census *Current Industrial Reports* (1997) series shows the total production and total shipment of nitrogen fertilizers (product codes 2873 ---) in short tons in 1994. Multiplying total shipments[13] by the nitrogen weight fraction, for each product class (see below) results in a total of 16.6 million short tons of N produced in 1994. In 1992, 79% of nitrogenous fertilizers (products with a code of 2873 ---) were produced in SIC 2873 (Bureau of the Census, *1992 Census of Manufacturers, Agricultural Chemicals* 1995). Hence, I assume that SIC 2873 produced $16.6 \cdot 0.79 \cdot 2000 = 26.2$ billion lbs of N in 1994.

The resulting energy-in/product-out ratio is about = 22,000 BTU/lb. However, for three reasons, this is a lower bound on total energy requirements for the manufacture of nitrogen fertilizer. First, it does not include the energy required to manufacture the materials that are input to SIC 2873. Second, it does not include any energy required for further processing of the output of SIC 2873. Third, the Census' estimate of the weight of shipments, which is the denominator of the BTU/lb estimate, probably overstates the net output of the industry. (See the discussion above in regards to phosphate fertilizers.) With these considerations, it does not seem unreasonable to that the true BTU/lb manufacturing energy requirement is 20% higher than the figure

[13]I use data on total shipments, rather than total production, because the latter includes production of intermediates that eventually are processed into and counted again as finished products.

just calculated. I assume that the average energy requirement, in BTU/lb, declines slightly over the projection period.

Energy mix. The EIA manufacturing energy consumption survey shows that 97.4% of the energy used in SIC 2873 in 1994 was natural gas, 2.1% was electricity, and 0.5% other fuels (EIA, *MCES 1994*, 1997). It is likely that energy uses at some of the other stages of the nitrogen-fertilizer fuelcycle (such as mining and transport) involve relatively more diesel fuel. Hence, I assume an overall breakdown of 96% natural gas, 2% electricity and 2% diesel fuel.

Fertilizer mixing, and transport of fertilizer product. See the discussion in the "Potash" section.

Ratio of material weight to nutrient weight. The ratio of material weight to nitrogen weight can be estimated as:

$$MNR = \frac{\sum_{N} W_N}{\sum_{N} W_N \cdot N_F} \qquad \text{eq. H.33}$$

where:

MNR = the ratio of material weight to nitrogen weight
W_N = the weight of nitrogen fertilizer material N shipped (from the Bureau of the Census *Current Industrial Reports* series, 1997)
N_N = the nitrogen weight fraction of fertilizer material N (calculated on the basis of the molecular formula: ammonia, 82% N; nitric acid, 22% N; ammonium nitrate, 35% N; ammonium sulfate, 21% N; and urea, 47% N)

With this formula, and assuming that 100%-N nitrogen solutions have a 2:1 material/nitrogen ration (the Census reports the weight of nitrogen solutions in terms of 100% N), I estimate that MNR = 1.82 for 1994. One gets a similar result, 1.89, by dividing the total amount nitrogen materials consumed in the U. S. in 1993 (21.5 million tons) by primary nitrogen consumption in 1993 (11.4 million tons), as reported by Taylor (1994). I will assume a value of 1.90.

Energy used to manufacture pesticides and seeds

Pesticides. Turhollow's (1997) update of Bhat et al. (1994) is the most comprehensive and recent estimate of energy embodied in agricultural pesticides. Bhat et al. (1994) proceed in four steps. First, they identify the pesticides most commonly used on major field crops in the U. S., and then group them according to their chemical structure. Next, they estimate the manufacturing energy required for each kind of pesticide. (These estimates, in GJ/Mg, are taken from Green's (1987) oft-cited contribution to the series *Energy in World Agriculture)*. Third, they calculate the application-weighted average energy content (GJ/Mg) for herbicides, insecticides, and

fungicides. Fourth, they add energy for formulation, packaging, and transport. Turhollow's updated result is about 105,000 BTU/lb for all pesticides[14].

In the chemical industry as a whole (SIC28), and in the miscellaneous organic chemicals industry, the breakdown of primary energy use is about 45% natural gas, 30% LPG, 8% electricity, 7% coal, and 10% oil (EIA, *Manufacturing Energy Consumption Survey,* 1994). However, Turhollow (1997) indicates a much larger share for oil. My assumptions are shown in Table H-28.

Seeds. I do not have data on the lifecycle energy requirements of seeds (excluding energy used for application, because that energy is included already in the farm fuel-use data). My assumption is shown in Table H-28.

Summary of estimates and assumptions regarding energy in the lifecycle of agricultural chemicals

Table H-28 summarizes the results of the analysis. The new, detailed estimates of emissions from the fertilizer lifecycle can be compared with the assumptions in DeLuchi (1993), with recent assumptions by the Fertilizer Institute (reported in Conway et al., 1994), and with Turhollow's (1997) updates (converted to 3412 BTU/kWh basis) of the detailed analysis by Bhat et al. (1994) (estimates in BTU/lb-nutrient):

	Nitrogen	P_2O_5	K_2O
Original Table K.3 (base year 2000)	25,000	3,000	3,000
Conway et al. (1994) (base year 1991)	22,160	4,176	1,244
Turhollow (1997) (base year 1987)	23,030	1680	1490

Miscellaneous energy data

In the previous model, the electricity share of the energy used to make fertilizer for wood-based fuels had an incorrect cell reference, with the result that the electricity share was incorrectly calculated to be zero. The correct cell reference and calculated value (about 0.10) results in a very slight increase in fuelcycle GHG emissions from wood-based fuels. The reference and value shown for the electricity share for ethanol from corn were correct.

Chemical-process and "fugitive" emissions of greenhouses

Although fuel combustion typically is the main source of GHG emissions in a fuelcycle, other chemical processes, or leaks of materials, also emit GHGs. For example, lime is produced by heating limestone to decompose the carbonate and drive off CO_2:

heat

[14]Ahmed et al. (1994) assume a somewhat higher figure of 180,000 BTU/lb.

$$CaCO_3 \text{ ----> } CaO + CO_2 \qquad \text{eq. H.34}$$

In this process, there are two sources of GHGs: the burning of the fuel to generate the heat for the decomposition, and the decomposition of the carbonate to CO_2. Emissions related to fuel use are accounted for the in the energy-use analysis of the preceding sections. The emission of CO_2 from the decomposition of the carbonate is an additional effect to be counted here.

In the reaction shown above, the production of one mole of lime, CaO, produces one mole of CO_2, and thus production of one gram of CaO (56.08 g/mole) releases 44.01/56.08 = 0.785 grams of CO_2 (44.01 g/mole). This amount of CO_2 is added to the "fertilizer manufacture" line of the analysis.

OTHER NOTES

In the LEM, all of the calculations of emissions from the assembly of vehicles and the manufacture of materials have been made more uniform and easier to follow.

Finally, note that the LEM does not estimate any emissions associated with vehicle recycling.

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TABLE H-1: EMISSIONS AND EFFLUENTS RESULTING FROM MATERIAL PRODUCTION AND MANUFACTURING AS A PERCENTAGE OF TOTAL FAMILY SEDAN LIFE CYCLE EMISSIONS

Air Emissions	
Particulates	65%
Sulfur Oxides	34%
Hydrogen Chloride	40%
Methane	26%
Water Effluents	
Metals	94%
Phosphates	97%
Oils	8%

Source: Sullivan et. al. (1998).

TABLE H-2: 1995 'GENERIC FAMILY SEDAN' MATERIAL BREAKDOWN BY WEIGHT

Material	% In car[a]	% U.S. consumption for cars[b]
Aluminum	6.32 %	18.9 %
Copper And Brass	1.65 %	10.0 %
Lead	0.85 %	69.5 %
Other Non-Ferrous Metals	0.18 %	23.0 % (zinc)
Polypropylene	1.71 %	—
Polyurethane	2.3 %	—
Polyvinyl Chloride	1.3 %	—
Other Plastics	3.99 %	3.2 %
Cast Iron	10.17 %	34.5 %
Virgin Steel	40.21 %	13.5 %
Recycled Steel	13.94 %	
Fluids	4.8 %	—
Glass	2.8 %	—
Rubber	6.9 %	62.9 %
Other Materials	3.3 %	—
Total	**100.42 %**	—

[a] **Sullivan et al. (1998). Total does not equal 100.00% due to independent rounding.** The 'generic family sedan' for which this is the material composition is a "synthesis of three comparable 1995 vehicles: the Dodge Intrepid, the Chevrolet Lumina, and the Ford Taurus." (Sullivan et. al., 1998, p.2) The generic vehicle was divided into three sections of roughly equal weight and each section was modeled using actual parts specifications from one of these three vehicles. The weight of the complete generic vehicle is 1532 kg (3370 lbs).

[b] **Graedel and Allenby (1998).**

TABLE H-3. PROJECTED MATERIALS COMPOSITION AND WEIGHT OF VEHICLES AS A FUNCTION OF FUEL ECONOMY

mpg, city cycle	**0.0**	**15.0**	**24.0**	**28.5**	**50.0**	**58.0**	**71.5**	**101.0**	**500.0**
weight empty (lbs)[a]	*6,000*	*4,500*	*3,600*	*3,350*	*2,981*	*2,641*	*1,975*	*1,781*	*1,700*
Virgn plain-carbon steel	0.46	0.41	0.37	0.32	0.25	0.17	0.18	0.00	0.00
High-strength steel	0.02	0.04	0.06	0.08	0.18	0.07	0.00	0.00	0.00
Stainless steel	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Recycled plain-carbon steel)[b]	0.20	0.18	0.16	0.14	0.00	0.07	0.08	0.00	0.00
Iron	0.16	0.15	0.14	0.13	0.07	0.00	0.00	0.00	0.00
Advanced composite	0.03	0.04	0.06	0.08	0.10	0.25	0.09	0.37	0.40
Other plastics	0.01	0.02	0.03	0.04	0.05	0.12	0.05	0.19	0.20
Fluids & lubricants)[c]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rubber	0.02	0.04	0.04	0.05	0.05	0.05	0.07	0.09	0.08
Virgin aluminum	0.01	0.01	0.02	0.03	0.06	0.07	0.14	0.04	0.04
Recycled aluminum)[b]	0.03	0.02	0.03	0.06	0.11	0.12	0.26	0.08	0.07
Glass	0.02	0.02	0.03	0.03	0.03	0.01	0.02	0.05	0.05
Virgin copper	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
Recycled copper)[b]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc die castings	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.07	0.07
Powdered metal components	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01
Virgin lead	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.03
Recycled lead)[b]	0.01	0.03	0.02	0.01	0.02	0.02	0.02	0.06	0.06

a The empty weight is without passengers or payload, but with a full fuel tank.

b We assume that in an automobile, 66% of the aluminum, 70% of the lead, 0% of the copper, and 30%of the plain carbon steel is recycled. These figures are discussed briefly in the text.

c In the LEM, the lifecycle of gasoline and lube oil are treated separately. The weight of these is deducted from the total empty weight, and the remaining weight is distributed among materials as shown. This means that the weight of other fluids (such as brake oil, transmission oil, and glues) is distributed to the other materials categories.

TABLE H-4. MATERIALS IN ELECTRIC VEHICLE BATTERIES

Material	Weight fraction of materials in each battery		
	Pb/acid[a]	*NiMH*[a]	*Li/polymer*[b]
Plain carbon steel	0.00	0.00	0.19
Hi-strength steel	0.00	0.00	0.00
Stainless steel	0.00	0.29	0.24
Recycled steel	0.00	0.00	0.05
Iron	0.00	0.15	0.00
Advanced composites	0.02	0.02	0.10
Other plastics	0.04	0.03	0.20
Fluids	0.14	0.06	0.00
Rubber	0.00	0.00	0.00
Aluminum	0.00	0.05	0.01
Glass	0.02	0.00	0.00
Virgin copper	0.01	0.01	0.01
Recycled copper	0.00	0.00	0.00
Zinc die castings	0.00	0.04	0.00
Powdered metal	0.00	0.00	0.00
Virgin lead	0.21	0.00	0.00
Recycled lead	0.48	0.00	0.00
Sodium	0.00	0.00	0.00
Sulfur	0.00	0.00	0.00
Titanium	0.00	0.04	0.00
Sulfuric acid	0.08	0.00	0.00
Potassium hydroxide	0.00	0.09	0.00
Nickel	0.00	0.22	0.00
Lithium	0.00	0.00	0.20
Total	*1.00*	*1.00*	*1.00*

a From Gaines and Singh (1995). Nickel-metal/hydride is of "AB_2" design (e.g., Ovonic). Patyk and Reinhardt (n.d.) give a slightly different breakdown for Pb/acid: 0.54 for lead or lead oxide, 0.198 for sulfuric acid, 0.12 for water, and 0.145 for plastics. By comparison, the

UC Davis battery cost and performance models indicate the following (Lipman, 1999a; models documented in Lipman, 1999b, and Burke, 1999):

Lead acid 12V,75Ah, monoblock (6 cells/module)	
lead grids	3.6 kg
lead oxide	5.8 kg
spongy lead	5.4 kg
sulfuric acid	5.3 kg
separator	0.16 kg
terminals (stainless steel)	0.07 kg
containment (stainless steel or plastic)	0.21 kg
Total	*20.5 kg*
NiMH 12V, 100Ah, monoblock, Gen3 (10 cells/module)	
anode grid (nickel-plated steel)	0.15 kg
cathode foam (pure nickel)	0.91 kg
metal hydride (nickel, vanadium, chromium, titanium, zirconium)	2.6 kg
nickel hydroxide	3.7 kg
cobalt oxide	0.11 kg
KOH	2.0 kg
separator	0.07 kg
grid tabs	0.2 kg
terminals (stainless steel)	0.05 kg
containment (stainless steel)	1.3 kg
Total	*11.1 kg*

For Pb/acid, this results in 72% lead, 26% sulfuric acid and water, and 2% plastic or stainless steel and other, which is reasonably close to the breakdown of Gaines and Singh (1995). We assume that most of this lead is recycled lead (as mentioned in the text). It is difficult to compare the estimates for NiMH because the UC Davis model does not breakdown composite materials such as nickel-plated steel, or hydroxides.

b My assumptions.

TABLE H-5. PROJECTED MARKET SHARE OF BATTERIES BY EV MODEL YEAR

Year	Pb/acid	NiMH	Li/poly.	Year	Pb/acid	NiMH	Li/poly.
1970 - 96	1.00	0.00	0.00	2026	0.03	0.20	0.77
1997	0.98	0.02	0.00	2027	0.03	0.20	0.77
1998	0.96	0.04	0.00	2028	0.03	0.20	0.77
1999	0.92	0.08	0.00	2029	0.03	0.20	0.77
2000	0.85	0.15	0.00	2030	0.03	0.20	0.77
2001	0.75	0.25	0.00	2031	0.03	0.20	0.77
2002	0.65	0.35	0.00	2032	0.03	0.20	0.77
2003	0.50	0.45	0.05	2033	0.03	0.20	0.77
2004	0.40	0.50	0.10	2034	0.03	0.20	0.77
2005	0.30	0.55	0.15	2035	0.03	0.20	0.77
2006	0.25	0.60	0.15	2036	0.03	0.18	0.79
2007	0.20	0.60	0.20	2037	0.03	0.18	0.79
2008	0.15	0.60	0.25	2038	0.03	0.16	0.81
2009	0.12	0.55	0.33	2039	0.02	0.16	0.82
2010	0.11	0.55	0.34	2040	0.02	0.16	0.82
2011	0.10	0.52	0.38	2041	0.02	0.14	0.84
2012	0.09	0.50	0.41	2042	0.02	0.14	0.84
2103	0.08	0.45	0.47	2043	0.02	0.12	0.86
2014	0.07	0.40	0.53	2044	0.01	0.12	0.87
2015	0.06	0.35	0.59	2045	0.01	0.10	0.89
2016	0.06	0.30	0.64	2046	0.01	0.10	0.89
2017	0.05	0.25	0.70	2047	0.01	0.08	0.91
2018	0.05	0.25	0.70	2048	0.01	0.08	0.91
2019	0.05	0.25	0.70	2049	0.01	0.06	0.93
2020	0.04	0.20	0.76	2050	0.01	0.06	0.93
2021	0.04	0.20	0.76				
2022	0.04	0.20	0.76				
2023	0.03	0.20	0.77				
2024	0.03	0.20	0.77				
2025	0.03	0.20	0.77				

Source: my estimates. See the text for a bit more detail.

TABLE H-6: LEM ESTIMATES OF THE AMOUNT AND KIND OF INPUTS REQUIRED TO MAKE A POUND OF MATERIALS

A. ENERGY INPUTS (U. S. VALUES)

Material	Energy (BTU/lb)[a]	distribution of energy by type (used in industrial boilers)				EOL recycle
		Coal	*Oil*	*NG*	*Power*[b]	
Virgin carbon steel[c]	7,500	other input	11.0%	60.0%	29.0%	0.90
High strength steel[d]	20% higher than plain carbon	other input	10.0%	58.0%	32.0%	0.90
Stainless steel[e]	100% higher than plain carbon	other input	9.0%	55.0%	36.0%	0.90
Recycled carbon steel	60% of virgin	24.7%	23.4%	37.6%	14.3%	0.90
Cast iron	16,663	72.4%	8.6%	15.1%	3.9%	0.90
Advanced composite[d]	80,000	0.0%	50.0%	50.0%	0.1%	n.e.
Other plastics[f]	63,742	0.0%	50.0%	50.0%	0.1%	0.00
Fluids & lubricants[g]	0					
Synthetic rubber[f]	39,460	0.0%	76.0%	23.3%	0.7%	0.00
Virgin aluminum[h]	93,000	1.0%	15.0%	30.0%	54.0%	0.85
Recycled aluminum[h]	16,000	0.0%	8.0%	76.0%	16.0%	0.85
Glass	8,089	0.0%	0.0%	94.6%	5.4%	0.00
Virgin copper	40,000	7.2%	35.9%	35.9%	21.0%	0.95
Recycled copper[i]	25% of virgin	7.2%	35.9%	35.9%	21.0%	?
Zinc die castings	32,743	35.0%	0.2%	54.0%	10.0%	n.e.
Powdered metal	4,000	4.0%	38.0%	29.0%	29.0%	n.e.
Virgin lead[k]	12,000	20.0%	10.0%	40.0%	30.0%	0.95
Recycled lead[k]	20% of virgin	20.0%	10.0%	40.0%	30.0%	0.95
Nickel	50,000	0.0%	100.0%	0.0%	0.0%	n.e.
Sodium[l]	15,658	25.9%	1.1%	0.0%	73.0%	n.e.
Sulfur	-					
Titanium[l]	60,498	3.0%	18.0%	10.0%	69.0%	n.e.
Sulfuric acid[m]	500	50.0%	10.0%	30.0%	10.0%	n.e.
Potassium hydroxide[n]	4,650	0.0%	10.0%	20.0%	70.0%	n.e.
Nickel	50,000	0.0%	100.0%	0.0%	0.0%	n.e.
Lithium[o]	1,000	50.0%	10.0%	30.0%	10.0%	n.e.
Cement[p]	1,500	55.0%	5.0%	30.0%	10.0%	n.e.
Concrete[p]	-					

Limestone[p]	300	10.0%	50.0%	30.0%	10.0%	n.e.
Lime[p]	-					
Refractories[q]	13,500	10.0%	20.0%	55.0%	15.0%	n.e.

LEM = Lifecycle Emissions Model; EOL = end-of-life fraction of material recycled (parameter EOLRF in eq. H.25); n.e. = not estimated. Note that these energy-use estimates do not include transportation of finished materials to end users. These transportation emissions are estimated and added separately.

[a] This is parameter ENR in eq. H.3. Energy inputs to each stage have been aggregated over the lifecycle of materials(from raw feedstock production through materials fabrication, excluding transportation, which is treated separately), using eq. H.8.

Generally, I have relied heavily on the estimates by EVTECA (ANL et al., 1998),Yoshiki-Gravelsins (1993), and Hudson (1982).

Note that these are values for the U. S. Values for other major material-producing countries are estimated relative to these U. S. values. See the text for more discussion.

[b] In this table, electricity is counted at 3412 BTUs/kWh. The LEM properly accounts for full lifecycle emissions from electricity use, starting with this 3412 BTU/kWh assumption.

[c] Energy data from the EVTECA (ANL et al., 1998) analysis, counting only natural gas, oil, and electricity inputs. (The EVTECA analysis also includes coal used for coking, blast-furnace and coke-oven gas, limestone, and refractories, but these are all treated separately here as non-energy inputs.) EOL recycling estimate based on Young and Vanderburg (1994) and Das (2000).

[d] My assumptions.

[e] Fuel distribution is my assumption, based in part on Hudson (1982).

[f] The EVTECA (ANL et al., 1998) input data discussed below do not show any electricity input, but I assume that there is a minor amount of electricity used to run plant equipment.

[g] In the LEM, the lifecycle of gasoline and lube oil are modeled separately, and brake fluid and transmission fluid are not considered explicitly.

[h] Energy data based mainly on Weston et al. (1998). Our estimate of the distribution of energy is based on our detailed reconstruction of the input-output flows in Weston et al. (1998), combining primary and secondary production. Recycling estimates based on Young and Vanderburg (1994), Stodolsky et al. (1995), and Das (2000).

[i] I assume that the energy mix for recycled copper is the same as that for virgin copper.

[j] My assumption, based partly on Hudson's (1982) estimate for "sound deadener". '

k Fuel distribution shares based partly on Hudson (1982). I assume that recycled lead has same fuel mix as virgin lead.

l Based on Hudson's (1982) estimates for the year 2000. See also Appendix P of DeLuchi (1993).

m I assume that the total BTU/lb energy requirement for making sulfuric acid is slightly more than that for sulfur (Tables P.3 and P.4 of DeLuchi [1993]), and that the energy breakdown of this total is the same as for sulfur (Table P.4 of DeLuchi [1993]; breakdown for sulfur changed slightly).

n I assume that the total BTU/lb energy requirement for making potassium hydroxide is 4,650 (Gaines and Singh, 1995), and that the energy breakdown of this total is the same as for potash (Appendix K of DeLuchi, 1993).

o I assume that the total BTU/lb energy requirement for making lithium is twice that of sulfur (as given in DeLuchi, 1993), and that the energy breakdown of this total is the same as for sulfur.

p See the discussion in the text in this appendix.

q BTU/lb value based on data from the EVTECA project (ANL et al., 1998). Distribution of energy is my assumption.

B. NON-ENERGY INPUTS, PER LB. OF MATERIAL

MATERIAL	Item #1			Item #2			Item #3		
Plain carbon steel[a]	1.05	lbs.	coking coal	0.13	lbs.	lime	0.015	lbs.	refractories
High-strength steel[a]	1.05	lbs.	coking coal	0.13	lbs.	lime	0.015	lbs.	refractories
Virgin stainless steel[a]	1.05	lbs.	coking coal	0.13	lbs.	lime	0.015	lbs..	refractories

These are the values for prameter OIR in eq. H.4. Inputs to each stage have been aggregated over the lifecycle of materials(from raw feedstock production through materials fabrication, excluding transportation, which is treated separately), using an analog of eq. H.7.

[a] Coking coal: The input/output values for coking coal are calculated from data in ANL et al. (1998) for making steel parts, presumably of plain carbon steel. I assume that the input/output ratios for high-strength steel and stainless steel are the same as those for plain carbon steel. In the LEM lbs. of coal input per lb. of material are converted to BTUs of coal input per lb. of materal assuming 24.6 10^6 BTU per ton of coking coal (based on IPCC [1997]).

Lifecycle emission associated with the use of coking coal are calculated the same way as are lifecycle emissons associated with the use of coal in industrial boilers (see the main report and DeLuchi [1993]), except with carbon content and emission factors specific to coking coal use. Coking coal is assumed to be 71% C by weight (IPCC, 1997). Emission factors for coking coal use are estimated from data in AEA Technology (2002), discussed next.

AEA Technology (2002) shows g/kg emission factors for coke production, from which I derive lb./ton-coal and g/10^6-BTU-coal emission factors, assuming 1.4 tons-coal/ton-coke (ANL et al., 1998) and 24.6 million BTU/ton-coking-coal (based on the IPCC [1997]):

Units	CH_4	CO	NO_X	SO_2	NMVOC	PM_{10}
g/kg coke made	0.081	4.6	-	-	0.018	0.0559
g/kg coal consumed	-	-	0.04	0.02	-	
lb/ton-coal	0.116	6.571	0.080	0.040	0.026	0.080
g/10^6 BTU-coal	2.14	121.28	1.48	0.74	0.47	1.47

The g/10^6-BTU factors shown above are used in the LEM. In addition, I assume 7.0 g-N_2O/10^6-BTU-coking coal. This is about twice the rate of emission from the use of coal in industrial boilers. As discussed in Appendix F, N_2O formation appears to increase at lower temperatures, and I assume that the use of coking coal in steel making is a lower-temperature process than is the combustion of coal in industrial boilers.

Limestone: The input/output value for limestone is calculated from data in ANL et al. (1998) for making steel parts, presumably of plain carbon steel. I assume that the

input/output ratios for high-strength steel and stainless steel are the same as those for plain carbon steel.

Refractories. Refractories are the bricks that line the furnaces and ladles that are used to handle molten steel. A "Cermamic Industry" newsletter says that "the average refractory consumption rate by the steel industry in China is reportedly high (possibly 20-30 kg of refractories per ton of steel produced), compared with 9.5-10 kg/ton in Japan and the U.S." (www.ceramicindustry.com/CDA/ArticleInformation/features/BNP__Features__Item/0,2710,61637,00.html). Similarly, a report in "Investment World" (Sunday, April 30, 2000, online) states that in India in 1998-99 "the specific consumption of refractories per tonne of liquid steel...declined by over 40 per cent to 20/21 kg (even down to 12-15 kg in a few modern efficient steel plants) from around 36 per kg in just over a decade" (www.blonnet.com/iw/2000/04/30/stories/0530e051.htm). These figures are consistent with aggregate annual consumption and production data: U. S. refractories production is 3-4 million tonnes annually, of which about 60% goes to steel, and U. S. steel production is on the order of 100 million tonnes annually (same "Ceramic Industry" source previously cited). Thus, it appears that in advanced industrial countries refractory use is about 0.010 to 0.015 tons per ton of steel, and that in less industrially advanced countries the figure is about 0.02.

TABLE H-7: SOURCES USED IN OUR ESTIMATES OF ENERGY INPUTS TO THE PRODUCTION OF MATERIALS FOR MOTOR VEHICLES (BTUS/LB-MATERIAL)

Material	Yoshiki-Gravelsins (1993)[a]	EVTECA (ANL et al., 1998)	Stodolsky et. al. (1995)	Gaines & Singh (1995)	Das et. al. (1995)
Virgin steel	17960	24800[c]	28140	28050[d]	27500
Recycled steel	8580		22510		16800
Stainless steel					
Cast iron	14620-19000	19000	16020	19000	
Virgin aluminum	48370-120930	97250	100000		147000
Recycled aluminum	11500-26800	19200	19050		26800
Polypropylene	31993-36400	34168		34000	
Polyurethane	41830-52100				
Polyvinyl chloride	37700-38690				
Other plastics	34000-42600	34000	34200	34000	32900-47400
Synthetic rubber	29075-68350	38283	38100		66100
Float glass	5630-12900			9450	23700
Textile glass	10000-11150			11150	
Virgin copper	23170-80470	60000	60600	60000	54500
Recycled copper	15150-17500		15150		17500
Virgin lead	11700-22520	11700		11700	14700
Recycled lead	500-2300	2300		2300	500
Nickel	52500	52500		52500	

Material	Sullivan & Hu (1995)	Han (1997)	Weir & Muneer (1998)	Wheeler (1982)	Hudson (1982)[b] BTU_{th}/BTU_e
Virgin steel	17243	17260[e]		27500	19945/15338[f]
Recycled steel					10550/8113[f]
Stainless steel					30437/24258[g]
Cast iron	14620	15750		5400	10130/9350
Virgin aluminum	84400	84000	97400	119300	120738/70028
Recycled aluminum	11200		21600	43300	24500/14210
Polypropylene	31993				
Polyurethane					
Polyvinyl chloride					
Other plastics					64598/61433
Synthetic rubber	29075	68350			46830/38307[h]
Float glass	12900	8360[i]	8050		9250/8408
Textile glass					
Virgin copper	43000	25560			65925/52081
Recycled copper					17170/13564
Virgin lead	17700	22520			15614/9275[j]
Recycled lead					6900/4099
Nickel					40725/32743[k]

As much as can be determined, the sources cited in this table count electricity in terms of the thermal input -- generally around 10500 BTUs/kWh (BTU_{th}) -- rather than at 3412 BTU/kWh (BTU_e).

In addition, Bouman (1998) reports a value of 8,040 BTU/pound of virgin molten steel (rolling and parts fabrication are not included). Cummings-Saxton (1982) reports a value of 24,800 BTU/lb of virgin steel, a value of 161,900 BTU/lb of virgin aluminum, and values of 24,400 BTU/lb and 88,800 BTU/lb for fiber-reinforced plastics and carbon composite plastics, respectively. The Cummings-Saxton numbers include transportation energy as well as parts manufacture. Griffiths (1996) reports values of 15,580 BTU/lb of virgin steel, 77,920 BTU/lb of virgin aluminum, and 5,630 BTU/lb of glass.

Recently, U. S. Automotive Materials Partnership has sponsored detailed analyses of the lifecycle of steel, aluminum, and plastics. Final results for aluminum and preliminary results for steel are available. Our reconstruction of the data for aluminum in Weston et al. (1998) indicate about 93,000 BTU/lb to produce primary cast aluminum (parameter E1 in eqs. H.1 and H.2; upper bound energy estimate) and 16,000 BTU/lb to produce secondary (recycled) cast aluminum (parameter E2 in eqs. H.1 and H.2). (These results are based on 3412 BTU/kWh for electricity.)

The preliminary results for steel are not detailed enough to be of use here.

[a] This source does not include parts fabrication energy.

[b] My calculations based on the equation and year-2000 parameter values in Hudson (1982). (See also DeLuchi (1993), appendix P.) The first estimate counts electricity at about 11,000 BTUs/kWh. The second estimate counts electricity at 3412 BTUs/kWh.

[c] In the text, this value is given as 33,000 BTU/lb, but the flow charts indicate the value in this table.

[d] This value is given in the text of this paper, but the value of 33,000 BTU/lb is given in a table in this paper.

[e] This value represents steel that is 62% basic oxygen furnace process and 38% electric arc furnace process.

[f] For cold-rolled steel.

[g] Virgin stainless steel. Hudson (1982) assumes that in 2000 85% of stainless steel is virgin.

[h] 65% virgin material, 35% reprocessed scrap. The results for virgin material are: 65,673/53,720; the results for scrap are 11,836/9,682.

[i] This value represents glass that is 75% virgin and 25% recycled from cullet (crushed glass).

[j] Battery lead.

[k] 61% virgin material, 39% reprocessed scrap. The results for virgin material are: 73693/50885; the results for scrap are 17,000/11,738.

TABLE H-8: PROCESS EMISSIONS RESULTING FROM MANUFACTURING A TON OF MATERIALS FOR AUTOMOBILES: ASSUMPTIONS IN THE LEM

Material	Process emissions (lb/ton)								
	NO_X	SO_X	CO	LEAD	PM_{10}	TSP[a]	CO_2	CH_4	NMVOCS
Virgin Steel	0	1.99	0.105	0	?	4.20	259	0.02	0
Cast Iron	0	0.156	145.0	0	0	3.451	0	0.0026	0.096
Recycled Steel	0.034	1.67	0.0068	0	0	0.512	34.16	0.0001	0.0017
Virgin Aluminum	4.3	30.4	135	0	15.68	75.11	3300	0.13	0.5
Recycled Aluminum	0	0	0	0	0	2.639	0	0	0.2
Synthetic Rubber	4.3	8	0.83	0	?	2.0	5180	0.19	11.6
Float Glass	8	1.8	0	0	?	1.0	300	0	0
Textile Glass	23	16	2.7	0	?	0	1020	0	0
Virgin Copper	0	800	0	0.2	?	86	0	0	0
Plastics (misc.)	8.2	45	1.3	0.0012	?	4	7817	0.29	0.49
Virgin Lead	0	4.5	0	0.07	?	0	0	0	0
Recycled Lead	0	8	0	0.29	?	0.71	0	0	0

Source: see the discussions in the text and the tables for each material, below. These values are used in the LEM. The LEM also has the following assumptions for PFC emissions from aluminum production:

	GWP	lb/ton
CF4	6500	0.80
C2F6	9200	0.08
HF	2000	1.13

The lb/ton emissions assumptions for these PFCs are based on the data presented in Table H-15. The GWPs ("Global Warming Potentials," which equate the warming impact of each PFC to that of CO_2, over 100 years) are from the IPCC (1996).

[a] For the purpose of calculating CO2-equivalent emissions, the LEM has CEFs for three classes of PM: PM from fossil-fuel combustion, PM from biomass combustion, and PM-dust (Appendix D). Generally, combustion PM comprises black carbon and organic matter, and dust comprises earth-crustal material. Lacking data to the contrary, I have assumed that all PM emissions reported here are combustion-like.

TABLE H-9: COMBUSTION EMISSIONS RESULTING FROM MANUFACTURING A TON OF MATERIALS FOR AUTOMOBILES (FOR REFEFRENCE ONLY)

Material	Combustion emissions (lb/ton)								
	NO_X	SO_X	CO	LEAD	PM_{10}	TSP	CO_2	CH_4	NMVOCS
Virgin Steel	3.59	11.53	0.511	0.000028	?	1.61	2737	0.68	0.23
Cast Iron	22.91	39.74	0.699	0.016	0	3.370	9690	0.0425	0.377
Recycled Steel	2.4	9.7	0.434	0.000028	0	1.23	1956	0.676	0.0884
Virgin Aluminum	30.47	88.88	3.24	0.000766	39.7	10.48	14394	0.422	0.441
Recycled Aluminum	18.45	73.61	3.026	0	?	9.257	10524	0.403	0.22
Synthetic Rubber	3.0	33	0.37	0.0011	?	1.5	1820	0.07	0.1
Float Glass	3.1	12.3	0.49	0	?	1.5	1800	0.045	0.4
Textile Glass	2.4	9.6	0.4	0.0004	?	1.2	1400	0.037	0.035
Virgin Copper	19.9	39.5	11.2	0.001	?	6.4	8120	0.21	2.47
Plastics (total)	8.2	45	1.3	0.0012	?	4	7817	0.29	0.49
Virgin Lead	16.4	28.1	0.47	0.012	?	1.9	6600	0.023	0.07
Recycled Lead	1.3	3.7	0.17	0.0001	?	0.46	840	0.032	0.046

Source: see the discussions in the text and the tables for each material, below. Note that the LEM does not use these values; rather, it calculates combustion emissions based on emission factors for boilers and other combustion devices. Furthermore, the values calculated by the LEM are not necessarily the same as the values shown here.

TABLE H-10. FUEL ENERGY CONTENT USED IN SOME OF THE CALCULATIONS IN THIS APPENDIX

Fuel	10^6 BTU	unit
Anthracite coal	25.4	ton
Bituminous coal	25.0	ton
Metallurgical coke	31.5	ton
Gasoline	0.130	gallon
Distillate fuel oil	0.139	gallon
Residual fuel oil	0.150	gallon
Natural gas	0.0010	cubic foot
Electricity	0.0105	kWh
Coke breeze	21.0	ton
Steam (low pressure)	1.0	1000 pounds
Steam (medium pressure)	1.4	1000 pounds

Source: Information taken from Table 1, Kusik et. al. (1982). Values in the LEM are similar.

TABLE H-11. ENERGY REQUIREMENTS FOR PRODUCTION OF COMMODITIES CONSUMED IN THE PRODUCTION OF AUTOMOTIVE MATERIALS (BTU/TONS)

Material	Gas	Oil	Coal	Elec.	Other	Total
Limestone	12000	173000	4000	38000	11000	238000
Lime	2373000	327000	2358000	372000	21000	5450000
Fluorspar		1090000				1590000
Met. Coke	3480000	200000	37700000	710000	-10590000	31500000
Iron ore	24000	405000		263000	21000	713000
Iron pellets	375000	527000		1254000	465000	2621000
Iron sinter	150000			320000	2000000	2470000
Oxygen				4410000		4410000

Material	BTU/ton
Breeze	21000000
Refractories	26600000
Carbon electrodes	160000000
Explosives	60000000
Caustic soda	30000000
Pitch	160000 (per gallon)
Anthracite	25940000
Cryolite	155000000
Aluminum fluoride	51400000

Source: Information taken from Table 2 in Kusik et. al. (1982).

TABLE H-12. INPUTS AND OUTPUTS AND EMISSIONS FOR VIRGIN STEEL PRODUCTION

Material	Inputs	Units	Outputs	Units
Iron ore pellets	1.13	Ton		
Sinter	1.13	Ton		
Oxygen	2904	Cubic feet		
Refractories[a]	16,400,000	BTU		
Lime	256.2	lbs		
Coal[b]	1.05	Ton		
Natural gas	8,560,000	BTU		
Fuel oil 6/7	4,300,000	BTU		
Electricity[c]	581	kWh		
Steel scrap	0.478	Ton	0.708	Ton
Coke oven gas[d]	137,700	BTU	6,177,366	BTU
Blast furnace gas[d]	2,900	BTU	6,549,497	BTU
Steel parts			1	Ton

Emission	Combustion	Process	Units
NO_X	3.59	0	lb/ton
SO_X	11.53	1.99	lb/ton
CO	0.511	0.105	lb/ton
Lead	0.000028	0	lb/ton
PM_{10}	?	?	lb/ton
TSP	1.612	4.20	lb/ton
CO_2	2,737	259[e]	lb/ton
CH_4	0.680	0.023[f]	lb/ton
NMVOCs	0.228	0	lb/ton

Source for emissions data: EVTECA (ANL et al., 1998). The EVTECA report distinguishes process from combustion emissions for some (but not all) pollutants for some (but not all) stages of the steel lifecycle. Where EVTECA does not distinguish process from combustion emissions, I have used my judgment.

Sources for materials data: Coal value derived jointly from Table 2-1, Steel Technology Roadmap and the EVTECA report (ANL et al., 1998). All other values from EVTECA report (ANL et al., 1998).

[a] Refractories are the bricks that line the furnaces and ladles that are used to handle molten steel. The EVTECA report (ANL et al., 1998) lists 9.6 million BTUs of refractories per ton of

raw steel. This figure then gets compounded to 16.4 mllion BTUs per ton of stamped steel parts. Now, elsewhere in the EVTECA report, refractories manufacture is listed as requiring 27 million BTUs to make a ton of refractory product. If that value is correct, then according to the EVTECA report it takes about 0.36 tons of refractories per ton of raw steel made. However, as discussed in the notes to Table H-6.B, the true rate of refractories consumption is over an order of magnitude lower, 0.01-0.02 tons/ton-steel. I assume that the 27 million BTU/ton-refractory figure (13,500 BTU/lb.) is correct, because it is of the same order of magnitude as the values estimated for other materials (Table H-7). I assume that the implicit 0.36 tons-refractories/ton-steel is incorrect (see notes to Table H-6.B).

b Coal is a chemical feedstock, not a fuel for combustion; it provdes carbon for reduction of the metal. A small amount of the carbon in the coal ends up in steel, but most ends up as CO_2. See also note e.

c Most sources count electricity in terms of the thermal input to power generation -- about 10500 BTUs/kWh. In this analysis, I count electricity at 3412 BTUs/kWh, then perform a separate lifecycle analysis of electricity generation with respect to delivered kWh.

d The input gas is assumed to come from the output, and hence is not represented as an "external" fuel input. The output left over after input requirements are met is assumed to be marketed as a coproduct or flared. See the discussion in the text for more details.

e These are CO_2 emissions related to the difference between the carbon content of input iron and ore and the carbon content of the output steel.

IPCC (1997) recommends estimating emissions of CO_2 on the basis of the carbon content of the input coal, the carbon content of the iron ore less the carbon sequestered in the steel, and the CO2/C ratio:

$$CO2_{PROCESS,STEEL} = (OIR_{COAL} \times CC_{COAL} + ORR_{ORE} \times CC_{ORE} - CC_{STEEL}) \times 2000 \times 3.664$$

where:

$CO2_{PROCESS,STEEL}$ = process-area CO_2 emissions in the steel lifecycle (lbs-CO_2/ton-steel)
OIR_{COAL} = total input of coal per ton of steel (this table)
CC_{COAL} = the carbon content of coking coal (0.70; IPCC [1997], AEA Technology [2001])
OIR_{ORE} = total input of iron ore per ton of steel (this table)
CC_{ORE} = the carbon content of iron ore (0.04; my assumption, based in part on data from steel's [2003] detailed "steelmaking" fact sheet showing that a small amount of iron ore is in the form of siderite, $FeCO_3$)
CC_{STEEL} = the carbon content of steel (about 0.01; IPCC [1977]; AEA Technology [2001])
2000 = lbs./ton
3.664 = ratio of weight of CO_2 to C.

We adopt a variant of this method. We count CO_2 emissions related to the difference between the carbon content of the iron ore and the carbon content of steel as process-area emissions, here. We include CO_2 emissions from the use of coking coal as a reducing agent as part of the lifecycle emissions associated coking coal as an other (non-energy) input (Table H-6).

[f] The IPCC (1997) estimates the value for process CH_4 emissions to be 1.8 lbs/ton of steel. The reason for the discrepancy between the value listed in the EVTECA (ANL et al., 1998) report and the IPCC report's value is not clear.

TABLE H-13. INPUTS AND OUTPUTS AND EMISSIONS FOR RECYCLED STEEL PRODUCTION

Material	Inputs	Units	Outputs	Units
Hematite ore	1.74	Ton		
Steel scrap	1.10	Ton	0.72	Ton
Lime	0.08	Ton		
Alloys	0.012	Ton		
Refractories	0.030	Ton		
Carbon	345087	BTU		
Electrodes	89501	BTU		
Oxygen	120031	BTU		
Nitrogen	2	BTU		
Coke	270069	BTU		
Natural gas	6151680	BTU		
Diesel	78261	BTU		
Fuel oil	4306342	BTU		
Gasoline	446346	BTU		
Electricity	11959634	BTU		
Met. Losses			0.10	Ton
Non-met. Losses			0.86	Ton
Other losses			0.09	Ton
Cold rolled steel parts			1	Ton

Emission	Steltech total	EVTECA combustion	EVTECA process	Units
NO_X	4.37	2.4	0.0342	lb/ton
SO_X	1.64	9.7	1.674	lb/ton
CO	2.14	0.434	0.0068	lb/ton
Lead	?	0.000028	0	lb/ton
PM_{10}	1.86	0	0	lb/ton
TSP	?	1.231	0.512	lb/ton
CO_2	2442	1956	34.16	lb/ton
CH_4[(b)]	0.07	0.676	0.0001	lb/ton
NMVOCs	0.60[a]	0.0884	0.0017	lb/ton

Sources for emissions data: all values from Steltech Ltd. and EVTECA (ANL et al., 1998) reports. The Steltech report is based on Canadian data, which might at least partially explain the discrepancies between the emissions factors in the two reports.

In the EVTECA (ANL et al., 1998) report, combustion and process emissions were not separated for the EAF raw steel production process. I assumed that the values for this were process emissions, becomes most of the energy for this step in EAF steelmaking comes from electricity. Combustion emissions come from the other steps in steelmaking.

Sources for material data: all material inputs except fuel oil from Steltech report. Fuel oil value is partly derived from the EVTECA report (ANL et al., 1998).

[a] This value is for "organics" in the Steltech report.

TABLE H-14. INPUTS AND OUTPUTS AND EMISSIONS FOR RECYCLED CAST IRON PRODUCTION

Material	Inputs	Units	Outputs	Units
Iron ore pellets	0.104	ton		
Sinter	0.104	ton		
Steel scrap	0.87	ton		
Coal	1.85	ton		
Natural gas	1,194,925	BTU		
Electricity	52.4	kWh		
Coke oven gas (net)			1,0642,597	BTU
Blast furnace gas (net)			595,551	BTU
Iron castings			1	ton

Emission	Combustion	Process areas	Units
NO_X	22.91	0	lb/ton
SO_X	39.74	0.156	lb/ton
CO	0.70	145.0	lb/ton
Lead	0.016	0	lb/ton
PM_{10}	0	0	lb/ton
TSP	3.37	3.45	lb/ton
CO_2	9690	0	lb/ton
CH_4	0.0425	0.0026	lb/ton
NMVOCS	0.375	0.096	lb/ton

Sources: all values taken from the EVTECA report (ANL et al., 1998).

TABLE H-15. INPUTS AND OUTPUTS AND EMISSIONS FOR PRIMARY (VIRGIN) ALUMINUM PRODUCTION

Material	Inputs	Units	Outputs	Units
Bauxite ore	13.95	ton		
Explosives	1.25	lbs		
Lime	507	lbs		
Caustic soda	2487	lbs		
Aluminum fluoride	0.055	ton		
Cryolite	0.029	ton		
Natural gas	16,996,000	BTU		
Fuel oil 6/7	5,249,900	BTU		
Electricity	36,600	kWh		
Aluminum scrap			1.90	ton
Aluminum parts			1	ton

Emission	Combustion EVTECA[a]	Process EVTECA[a]	Process Al LCI[b]	Process IPCC[c]	Process other[d]	Units
NO_X	30.5	0.00	0.0	4.30	n.e.	lb/ton
SO_X	88.9	30.4	36.8	30.2	n.e.	lb/ton
CO	3.24	?	136	1,070	250	lb/ton
Lead	0.00077	0	0.0016	n.e.	n.e.	lb/ton
TSP/particulates	10.5	75.11	13.4	n.e.	15.7	lb/ton
CO_2	?	n.e.	3,380	3,300	3,000	lb/ton
CH_4	0.42	0	0.13	n.e.	n.e.	lb/ton
NMVOCs	0.44	0	0.5	n.e.	n.e.	lb/ton
Gaseous fluoride	0	11.7	n.e.	n.e.	n.e.	lb/ton
Particulate fluoride	0	7.7	n.e.	n.e.	n.e.	lb/ton
HF	0	1.13	1.2	n.e.	n.e.	lb/ton
C_2F_6	0	n.e.	0.06	$1/10^{th}$ CF_4	0.15	lb/ton
CF_4	0	n.e.	1.5	0.2-3.0	1.3	lb/ton
Red mud	0	3,800	n.e.	n.e.	n.e.	lb/ton
Spent liquid tds	0	152	n.e.	n.e.	n.e.	lb/ton
Spent pot liner	0	71	n.e.	n.e.	n.e.	lb/ton

n.e. = not estimated

a From EVTECA (ANL et al., 1998). EVTECA does not explicitly identify any CO or CO_2 emissions as being from process areas, but we believe that some of the CO_2 emissions probably are from process areas.

b From the lifecycle inventory of the aluminum industry by Weston et al. (1998), for primary shape cast aluminum.

c From the emission inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC, 1997). The IPCC (1997) takes its CO value from CORINAIR, a European emissions inventory program, and notes that the degree of control is not specified. It seems likely that these are uncontrolled CO emissions, some of which get controlled to CO_2.

The IPCC (1997) recommends a value of 3,600 lb-CO_2/ton-aluminum for the Soderberg process, and 3,000 lb-CO_2/ton-al for the prebaked anode process. I show the midpoint here.

d CO and particulates values from Margolis (1997). (Margolis (1997) also shows 39.7 lb-TSP/ton-aluminum from combustion.) CO_2, C_2F_6 and CF_4 values from EPA's *Inventory of U. S. Greenhouse Gas Emissions and Sinks 1990-1999* (2001), for the year 1990. The also EPA (2001) estimates that the 1999 CF_4 emission rate is about half the 1990 rate, and that the 1999 C_2F_6 emission rate is about 1/3 of the 1990 rate. I consider this change when I make my estimates for the LEM. EPA's (1995) AP-42 has emission rates for CO_2, C_2F_6 and CF_4 close to those of EPA (2001).

TABLE H-16. INPUTS AND OUTPUTS AND EMISSIONS FOR SECONDARY (RECYCLED) ALUMINUM PRODUCTION

Material	Inputs	Units	Outputs	Units
Fuel oil 6/7	5,249,900	BTU		
Natural gas	16,996,000	BTU		
Electricity	1,156	kWh		
Aluminum scrap			1.90	ton
Aluminum parts			1	ton

Emission	Combustion[a]	Process[a]	Process[b]	Units
NO_X	18.451	0	0.0	lb/ton
SO_X	73.61	0	0.0	lb/ton
CO	3.0261	0	0.0	lb/ton
Lead	0	0	0.0009	lb/ton
particulates	n.e.	0	0.0008	lb/ton
TSP	9.257	2.639	n.e.	lb/ton
CO_2	10524	0	0.0	lb/ton
CH_4	0.403	0	0.0	lb/ton
NMVOCS	0.22	0	0.2	lb/ton

Energy inputs and outputs from EVTECA (ANL et al, 1998).

a From the EVTECA (ANL et al., 1998).

b From the lifecycle inventory of the aluminum industry by Weston et al. (1998), for secondary shape cast aluminum.

TABLE H-17. INPUTS AND OUTPUTS AND EMISSIONS FOR POLYPROPYLENE PRODUCTION

Material	Inputs	Units	Outputs	Units
Propylene	1.05	ton		
Fuel oil	28,400,000	BTU		
Polypropylene			1	ton

Emission	Combustion and process areas	Units
NO_X	5.4	lb/ton
SO_X	30	lb/ton
CO	0.9	lb/ton
Lead	0.0008	lb/ton
TSP	2.64	lb/ton
CO_2	5200	lb/ton
CH_4	0.19[a]	lb/ton
NMVOCs	0.05[b]	lb/ton
Propylene	0.4[b]	lb/ton
Particulate	3[c]	lb/ton
Catalyst, treat. Beds (haz.)	0.2	lb/ton

Source: the EVTECA (ANL et al., 1998) report, for polypropylene polymerization, except as noted.

a The IPCC (1997) shows 2 lbs/ton for the production of ethylene, which is a component of polyethylene, which is similar to polypropylene.

b EPA's AP-42, Chapter 6.6.4., Organic Chemical Process Industry (EPA, 1995), shows an estimate of 0.7 lbs/ton for polypropylene emissions. The IPCC (1997) shows a range of 0.7 to 24 lbs.-VOCs/ton, and recommends the upper end of 24.

c From EPA's AP-42, Chapter 6.6.4., Organic Chemical Process Industry (EPA, 1995).

TABLE H-18. INPUTS AND OUTPUTS AND EMISSIONS FOR POLYESTER

Material	Inputs	Units	Outputs	Units
Mixed xylenes	0.79	ton		
Methanol	0.05	ton		
Ethylene glycol	0.7	ton		
Fuel oil	74,600,000	BTU		
Light ends			0.15	ton
Polyester			1	ton

Emission	Combustion and process areas	Units
NO_X	14.2	lb/ton
SO_X	79	lb/ton
CO	2.2	lb/ton
Lead	0.0021	lb/ton
TSP	7.04	lb/ton
CO_2	13,600	lb/ton
CH_4	0.5	lb/ton
NMVOCs	1.54[b]	lb/ton
Particulate (pet)[a]	0.34	lb/ton

Source: the EVTECA (ANL et al., 1998) report, for polyester production, except as noted.

a AP-42, Chapter 6, Organic Chemical Process Industry (EPA, 1995).

b AP-42 (EPA, 1995) gives a range of 0.72 to 1.48 for this value. The EVTECA (ANL et al., 1998) reported number falls outside of this range.

TABLE H-19. INPUTS AND OUTPUTS AND EMISSIONS FOR MISCELLANEOUS PLASTICS

Material	Inputs	Units	Outputs	Units
Fuel oil	42,800,000	BTU		
Plastic			1	ton

Emission	Combustion and process	Units
NOχ	8.2	lb/ton
SOχ	45	lb/ton
CO	1.3	lb/ton
Lead	0.0012	lb/ton
TSP	4	lb/ton
CO_2	7817	lb/ton
CH_4	0.29	lb/ton
NMVOCs	0.49	lb/ton
Vinyl chloride (PVC)[a]	17	lb/ton
Particulate (PVC)[a]	0.7	lb/ton

Source: the EVTECA (ANL et al., 1998) report, except as noted.

[a] AP-42, Chapter 6, Organic Chemical Process Industry (EPA, 1995).

TABLE H-20. INPUTS AND OUTPUTS AND EMISSIONS FOR SYNTHETIC RUBBER PRODUCTION

Material	Inputs	Units	Outputs	Units
Styrene	0.22	ton		
Butadiene	0.71	ton		
Soap	0.07	ton		
Fuel oil 6/7	38,400,000	BTU		
Synthetic rubber			1	ton

Emission	Combustion	Process areas	Units
NO_X	3.0	4.3	lb/ton
SO_X	33	8	lb/ton
CO	0.37	0.83	lb/ton
Lead	0.0011	0	lb/ton
TSP	1.5	2.0	lb/ton
CO_2	1820	5180	lb/ton
CH_4	0.07	0.19	lb/ton
NMVOCS	0.1	11.6	lb/ton

Sources: All values in these tables are taken from the EVTECA report (ANL et al., 1998).

TABLE H-21. INPUTS AND OUTPUTS AND EMISSIONS FOR FLOAT GLASS PRODUCTION

Material	Inputs	Units	Outputs	Units
Sand	0.73	ton		
Limestone	0.24	ton		
Soda ash	0.23	ton		
Electricity	1940000	BTU		
Natural gas	10080000	BTU		
Float glass			1	ton

Emission	Combustion	Process areas	Units
NO_X	3.1	8	lb/ton
SO_X	12.3	1.8	lb/ton
CO	0.49	0	lb/ton
Lead	0	0	lb/ton
TSP	1.5	1.0	lb/ton
CO_2	1800	300	lb/ton
CH_4	0.045	0	lb/ton
NMVOCS	0.4	0	lb/ton

Sources: all emissions data are taken from the EVTECA report (ANL et al., 1998). All materials data are taken from Ruth and Dell'Anno (1997).

TABLE H-22. INPUTS AND OUTPUTS AND EMISSIONS FOR TEXTILE FIBERGLASS PRODUCTION

Material	Inputs	Units	Outputs	Units
Sand	0.54	ton		
Limestone	0.19	ton		
Clay	0.34	ton		
Borate	0.15	ton		
Electricity	18280000	BTU		
Natural gas	2740000	BTU		
Textile fiberglass			1	ton

Emission	Combustion	Process areas	Units
NO_X	2.4	23	lb/ton
SO_X	9.6	16	lb/ton
CO	0.4	2.7	lb/ton
Lead	0.0004	0	lb/ton
TSP	1.2	0	lb/ton
CO_2	1400	1020[a]	lb/ton
CH_4	0.037	0	lb/ton
NMVOCS	0.035	0	lb/ton
Other GHGs	?	?	lb/ton
Fluorides	0	2	lb/ton

Sources: all emissions data are taken from the EVTECA report (ANL et al., 1998). All materials data are taken from Ruth and Dell'Anno (1997).

[a]The carbon dioxide process emissions value published by Ruth and Dell'Anno is 440 lb/ton. The reason for the discrepancy between these two data sources is not clear.

TABLE H-23. INPUTS AND OUTPUTS AND EMISSIONS FOR PRIMARY (VIRGIN) COPPER PRODUCTION

Material	Inputs	Units	Outputs	Units
Copper sulfide ore	164	ton		
Explosives	171	lb		
Lime	792	lb		
Steel balls/rods	300	lb		
Limestone	513	lb		
Silica ore	1640	lb		
Natural gas	28,300,000	BTU		
Fuel oil 6/7	26,000,000	BTU		
Electricity	5010	kWh		
Gold			0.25	troy oz.
Silver			10.5	troy oz.
Sulfuric acid			2.3	ton
Copper wire			1	ton

Emission	Combustion	Process area	Units
NO_X	19.9	0	lb/ton
SO_X	39.5	800	lb/ton
CO	11.2	0	lb/ton
Lead	0.001	0.2	lb/ton
TSP	6.4	86	lb/ton
CO_2	8120	0	lb/ton
CH_4	0.21	0	lb/ton
NMVOCS	2.47	0	lb/ton

Source: all values are taken from the EVTECA report (ANL et al., 1998).

TABLE H-24. INPUTS AND OUTPUTS AND EMISSIONS FOR PRIMARY (VIRGIN) LEAD PRODUCTION

Material	Inputs	Units	Outputs	Units
Lead sulfide ore	?	ton		
Coke	0.955	ton		
Lead			1	ton

Emission	Combustion	Process area	Units
NO_X	16.4	0	lb/ton
SO_X	28.1	4.5	lb/ton
CO	0.47	0	lb/ton
Lead	0.012	0.07	lb/ton
TSP	1.9	0	lb/ton
CO_2	6600	0	lb/ton
CH_4	0.023	0	lb/ton
NMVOCS	0.07	0	lb/ton

Sources: all values taken from the EVTECA report (ANL et al., 1998).

TABLE H-25. INPUTS AND OUTPUTS AND EMISSIONS FOR SECONDARY (RECYCLED) LEAD PRODUCTION

Material	Inputs	Units	Outputs	Units
Lead scrap	1	ton		
Fuel oil	4,600,000	BTU		
Lead			1	ton

Emission	Combustion	Process	Units
NO_X	1.3	0	lb/ton
SO_X	3.7	8	lb/ton
CO	0.17	0	lb/ton
Lead	0.0001	0.29	lb/ton
TSP	0.46	0.71	lb/ton
CO_2	840	0	lb/ton
CH_4	0.032	0	lb/ton
NMVOCS	0.046	0	lb/ton

Sources: all values taken from the EVTECA report (ANL et al., 1998).

TABLE H-26. TONS SHIPPED AND MILES/TON, FOR MOTOR VEHICLES AND MOTOR-VEHICLE PARTS, FROM THE 1997 *COMMODITY FLOW SURVEY*

SCTG	Rail	Truck	Water
341 (engines) – 1000 tons shipped	1,000	10,000	0
341 (engines) – miles/ton	912	361	
361 (cars) – 1000 tons shipped	12,000	12,000	0
361 (cars) – miles/ton	927	291	n.e.
362 (trucks) – 1000 tons shipped	400	4,000	300
362 (trucks) – miles/ton	688	647	973
364 (parts) – 1000 tons shipped	6,000	48,000	1,500
364 (parts) – miles/ton	645	342	n.e.

Source: 1000 tons shipped from the 1997 *CFS* (Bureau of the Census, 1999). Average miles per ton is my calculation equal to CFS-reported ton-miles divided by CFS-reported tons. Some tonnage was reported as being shipped by multiple modes; I distributed this tonnage to individual modes using my judgment.

TABLE H-27. CALCULATION OF TONS OF MOTOR VEHICLES PRODUCED

Car class	New sales in 1997 (thousands)[a]	Average weight per vehicle (lbs)[b]	Total weight (1000 tons) [c]
Passenger cars	8,273	3,000	12,400
Light trucks (GVW < 10,000 lbs)	6,781	3,800	12,900
Heavy trucks (GVW > 10,000 lbs)	430	21,000	4,500
All	*15,484*	*n.e.*	*32,200*

GVW = gross vehicle weight.

a From Morris (2001).

b Rough estimates based on Delucchi (1996).

c The product of sales and average weight.

TABLE H-28. THE ENERGY LIFECYCLE OF AGRICULTURAL AND OTHER CHEMICALS

Energy use BTU/lb[a]	**N**	**P_2O_5**	**K_2O**	**CaO**	**sulfur**	**pesticide**	**seeds**
Mining	n.e.[b]	334	1,942	n.e.	569	n.e.	n.e.
Mineral transport	n.e.[b]	339	179	n.e.	113	n.e.	n.e.
Manufacture	24,456	2,242	n.a.[c]	n.e.	n.a.[c]	n.e.	n.e.
Fertilizer mixing	224	79	389	n.e.	n.a.	n.e.	n.e.
Fertilizer transport	306	319	see mineral[d]	n.e.	see mineral[d]	n.e.	n.e.
Total	*24,985*	*3,314*	*2,509*	*620*[e]	*682*	*105,000*[e]	*2,500*[e]
Energy breakdown[f]							
Crude oil	0.00	0.00	0.00	0.00	0.00	0.07	0.00
Diesel and "other"[g]	0.00	0.30	0.04	0.45	0.05	0.20	0.02
Residual fuel oil	0.00	0.01	0.01	0.00	0.00	0.05	0.08
Natural gas	0.96	0.23	0.48	0.45	0.30	0.40	0.44
LPG	0.00	0.00	0.00	0.00	0.00	0.10	0.30
Coal	0.00	0.12	0.33	0.00	0.45	0.07	0.07
Electricity[h]	0.02	0.12	0.07	0.00	0.10	0.10	0.08
Gasoline	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diesel train	0.00	0.09	0.04	0.05	0.05	0.00	0.00
Fuel oil ship	0.00	0.02	0.01	0.01	0.01	0.00	0.00
Diesel truck	0.01	0.11	0.03	0.04	0.04	0.01	0.01
Total = 1.0?	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*	*1.00*

n.e. = not estimated; n.a. = not applicable.

a BTUs of energy (HHV) per lb of nutrient (N, P_2O_5, and K_2O) marketed. See the text for details.

b I do not estimate explicitly the energy required to produce and transport the inputs to nitrogen-fertilizer manufacturing plants; rather, I multiply estimated manufacturing energy by a factor meant to account for energy requirements of feedstock production and transport. See the text.

[c] There is no "manufacturing" stage as defined here; the mining establishments produce what I take to be the finished product (refined potassium chloride [KCl], or sulfur).

[d] The main potash fertilizer, KCl, and sulfur are classified as "fertilizer and chemical minerals" in the *1993 CFS* (Bureau of the Census, 1996) which provides the primary data on transportation tons and ton-miles by mode. See the text for discussion.

[e] These are assumed, not estimated values. See the text for details regarding CaO and pesticides. The value for seeds is my assumption. It results in a total estimated energy requirements for seeds that is of the same order of magnitude as that for pesticides, which is consistent with the data in Jensen and Hauggaard-Nielsen (2003; their Table 2).

[f] Energy breakdowns for N, P_2O_5, and K_2O are calculated from survey data on energy input, by kind, per unit of product output, for each stage of the fuelcycle. See the text for details. The energy breakdowns for the other chemicals are input assumptions, based in part on energy-input/product-output analysis.

[g] These are the "other" fuels in the EIA's *MCES 1994* (1997). I have assumed that in the aggregate they are equivalent to diesel fuel.

[h] Counted here at 3412 BTU/kWh. The main g/BTU and g/mi emission calculations in the model include full fuelcycle emissions from electricity generation (and from the lifecycle of the fuels used by the power plants).